ABSTRACT

Title of Thesis: Morphology in Urbanized Streams of the Puget Sound Lowland Region

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Increased runoff from urbanization may result in erosion to the stream channel and banks, leading to channel incision, bed changes, loss of instream debris and habitat, and an overall reduction of heterogeneity and channel complexity. These impacts are especially evident in low gradient, gravel-bed, meandering streams - the major type of stream in the Puget Sound Lowland region. The failure of many stream restoration projects is due to a lack of understanding of how morphological features of a stream respond to hydrological changes. Single cross-section methods (instead of reach-level) are generally used and may not adequately portray the complexity, or variation, of the stream channel and bed. Three main hypotheses in this thesis are: 1) a single cross-section taken within a reach does not adequately describe a stream compared to a mean value calculated from several measurements; 2) urban streams with more urbanized drainage areas have higher shear stresses, and thus move larger bed particles and have higher reach mobility; and 3) urban channels have less channel complexity than non-urban channels. Results showed that a single cross-section may not adequately describe the morphological variables of a stream reach; however, this method may be appropriate for calculating reach shear stress. In addition, shear stress and mobility were not found to increase with increasing

urbanization. Furthermore, complexity was not found to decrease with increasing urbanization. These two latter results indicate that urbanization (or percent imperviousness) alone cannot be used as a variable to investigate changes in stream morphology and hydraulics. In fact, a measure of sediment supply could be considered an additional independent variable by which to study urbanization impacts to streams. Substrate distributions from this thesis also support this finding.

MORPHOLOGY IN URBANIZED STREAMS OF THE PUGET SOUND LOWLAND REGION

By

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Symbols

1) Bankfull Width = BW
2) Bankfull Depth = BD
3) Coefficient of Variation = CV
4) Cross-Section Area = CS/CS Area
5) Hydraulic Radius = Hyd Rad
6) Relative Roughness (based on D_{50}) = d/D_{50}
7) Relative Roughness (based on D_{84}) = d/D_{84}
8) Size of 16 Percentile Substrate = D_{16}
9) Size of 50 Percentile Substrate = D_{50}
10) Size of 84 Percentile Substrate = D_{84}
11) Standard Deviation = SD
12) Substrate Heterogeneity = D_{84}/D_{50}
13) Substrate Sorting = $(D_{84}-D_{16})/2$
14) Width/Depth Ratio = W/D
15) Wetted Perimeter = WP

Introduction and Statement of Problem

Background

Population growth in the United States, along with a population shift out of agricultural/rural areas, has led to increased concentrations in urban areas and associated stresses on natural resources, especially aquatic ones. Although the location of water resources sometimes pose as an obstacle to development and new utility infrastructure, the aesthetic qualities of streams and lakes also make them prime locations for development. Thus, there is a continuous conflict between natural resource protection and development interests.

The conversion of agricultural and forestland to urbanized and sub-urbanized land uses impacts stream systems physically, biologically, chemically and aesthetically. Urbanization generally distorts and intensifies the natural processes of the watershed and its stream ecosystem through changes in watershed hydrologic conditions, channel morphological characteristics, chemical water quality, riparian zone integrity, and instream aquatic habitat. This is especially true in the Puget Sound area, where development and urban growth are, by far, the most influential land use practices affecting lowland streams (May, 1996). A large number of development projects were undertaken in this area without comprehensive planning; therefore, stream habitat and riparian zones have become degraded in the Puget Sound Lowland region.

It is known that stream systems tend to reflect the character of the watershed that they drain (Leopold, 1994). While each development project is usually implemented taking into consideration its impact on its surrounding stream area, their cumulative effects on entire watersheds are often neglected. Cumulative effects refer to changes in watershed and stream channel conditions caused by collective processes involved with urbanization, occurring over many decades, and distributed over the entire Puget Sound Basin at various levels (May, 1996). Since the 1960's, scientists have studied the individual and cumulative effects of urbanization on watershed hydrology and stream morphology (Leopold, 1968, 1992; Booth, 1991, 2000, 2002; Henshaw, 2000; May, 1996; McBride, 2001). The increase in stormwater runoff, sediment loads, and nonpoint source pollution is recognized as a major factor in urban stream system degradation (Schueler, 1994). Displacement of vegetation by impervious surfaces, such as buildings, roads, and parking lots, causes significant increases in runoff, which can result in a variety of impacts to stream channels. Hammer (1972) found that overland flows increased by as much as 50% because of urbanized surfaces.

The increased runoff may result in erosion to the stream channel and banks, leading to channel incision, bed changes, loss of instream debris and habitat, and an overall reduction of heterogeneity and channel complexity. These impacts are especially evident in meandering streams, where their alternating riffle-pool systems tend to decrease in number in urbanized areas and consequently reducing the amount of available habitat. Low gradient, gravel-bed, meandering streams are the major type of stream in the Puget Sound Lowland region, and thus, with the ever increasing population growth in this area, these impacts are becoming more common.

While there have been sporadic efforts at mitigating these effects, the current protection strategies employed have not achieved their goals. Existing regulations, water quality standards and best management practices (BMPs) intended to protect streams and watersheds have not been effective enough. As a result, urban streams continue to degrade (Booth, 1991; Schueler, 1994). The lack of understanding of these long term impacts has led many local and state governments to pay millions of dollars to mitigate their effects (MacRae, 1997). Moreover, even where governments have been willing to bear the burden, mitigation is limited because the majority of stream restoration projects are deemed as failures (MacRae, 1997).

The failure of many stream restoration projects is due to a lack of understanding of how morphological features of a stream respond to hydrological changes. Typically, measures of morphology are taken from one cross-section in order to describe a stream. Single cross-sections may not be enough to adequately portray and understand the complexity, or variation, of the stream channel and bed. Stream science practitioners usually carry out standardized measurement procedures, because a lack of resources limit their time on in the field and on projects. While this is understood by the authors, it is not clear whether present standards are adequate to assess stream degradation. The intent of this thesis is to determine if another procedure is more appropriate to investigate stream complexity.

Stream channel variation can be shown by its complexity, which can be generally defined by a variety of physical features or characteristics. One measure of channel complexity is the variation in channel width, depth, and area, as well as bed material, over a reach (represented by the standard deviation of these variables). Bedforms are also characteristic of channel complexity, with riffle-pool sequences as the main type in low gradient, gravel-bed streams. These sequences result from deposition and scour of stream bed material in organized patches along the channel length. These features can be quantitatively described as the bed amplitude (Prestegaard, 1983), the percentage of riffles and pools in the channel, and as changes in relative roughness along the channel (d/D_{50} or d/D_{84}). In this thesis, the author carries out a quantitative study of urbanization impacts to stream geomorphology by measurements such as those described to determine the complexity of the study sites. Coefficients of variation of morphology and hydraulic variables are used to measure complexity.

Hypotheses and Objectives

There are three main hypotheses in this study. The first hypothesis states that a single cross-section taken within a reach does not adequately describe a stream compared to a mean calculated from several measurements. Generally, practitioners use a single cross-section to describe a stream reach and possible degradation from land use, such as urbanization. This hypothesis states that this may not be sufficient.

The second hypothesis is that urban streams with more urbanized drainage areas have higher shear stresses, and thus move larger bed particles. Furthermore, reach mobility increases with increasing urbanization.

The third hypothesis is that, as a result of urbanization, urban channels have less channel complexity than non-urban channels. Thus, streams with higher shear stresses have less complex channels.

To test these hypotheses, I have designed the following objectives:

1) To urban land cover as a variable to describe impervious surfaces and determine an adequate measurement of urbanization to characterize the watershed;
2) To evaluate channel complexity;

3) To determine whether reach-averaged morphological and hydraulic stream parameters are significantly different from downstream (single) channel measurements; and
4) To assess the relationship between channel complexity and urbanization in the Region by the coefficients of variation of those reach-averaged variables.

Previous Work

General Urbanization Impacts (particularly in Puget Sound Lowland)

The urbanization of the Puget Sound Lowland Region has dramatically altered the natural flow regime and geomorphic conditions within stream systems. The adverse effects of development to streams have been documented work across the country (Leopold, 1968; Hammer, 1972; Dunne and Leopold, 1978; Arnold et al, 1982; Barker, et al, 1991; Booth, 1991; May, 1996; McBride, 2001). Additional impacts to streams include degraded water quality, as well as reduced riparian buffers, instream aquatic habitat, and headwater wetlands.

Development and urban growth are, by far, the most influential land-use practices affecting lowland streams in the Puget Sound Lowland region (PSL). The intensity of urban impact has been shown to be a direct function of the level of urbanization within the watershed (Schueler, 1994; Olthof, 1994). With urbanization, natural vegetation is altered or removed, hydrologic patterns are disrupted, soil is compacted, and areas of impervious surface are created (i.e. roads, roofs, etc.), replacing forested and wetland areas, as well as other more pervious areas. Booth (May, 1996) has found that construction in the beginning development process can remove up to one meter of soil through excavation and grading of the land.

The use of imperviousness as the basic measure of urbanization is based on the underlying relationship between the amount of impervious surface and the magnitude of runoff. Stormwater runoff represents the fraction of rainfall volume that is actually immediate streamflow. Runoff volume closely tracks with imperviousness, except at low levels where soils and slope factors tend to dominate the system and little or no runoff occurs (Schueler, 1994).

Urbanization can directly change instream morphological structure. In intensively urbanized areas, streams are often extensively modified to reduce the risk of flooding, prevent stream-side property loss due to erosion, and accelerate stormwater drainage. Stream channelization and "rip-rap" (streambank armoring) frequently accompany development in the more urbanized portions of the stream channel network. These modifications tend to exacerbate the flow-related changes within the stream system.

Urbanization Impacts to Stream Hydrology

Urbanization activities within a watershed can cause major changes in the local and regional hydrologic cycle. These include changes in the infiltration and runoff processes, reduced evapotranspiration due to removal of natural vegetation, alterations in groundwater and surface water interactions, and modifications of the surface water drainage network itself. These changes occur more rapidly and on a broader spatial scale than that which is typical of the natural flow regime characteristic of PSL streams. Many studies have documented changes to the flow regime in urban streams (Booth, 1991; Konrad, 2000).

A hydrologic regime is normally characterized by its predominant runoff process. The characteristic runoff process is determined by a combination of climate, topography, and physical features including vegetation, soil types, and underlying geology. In natural catchments, infiltration capacities of undisturbed soils are exceeded only during large, multi-day storm events which have the potential to saturate the groundwater table on hillslopes, resulting in excess surface runoff which flows directly into stream channels (saturated overland flow). Normally in the Puget Sound's hydrologic regime, most water flows to stream channels via subsurface routes, either within the surface soil layer or through deeper substrata pathways, and not as overland flow. This process may take several hours or days to accomplish (May, 1996).

Besides the increased runoff discussed above, there is a reduction in canopy interception, a decrease in evapotranspiration, reduced surface depression storage, and, most importantly, a significant decrease in surficial infiltration and deep percolation into the groundwater (May, 1996). Depression storage is reduced during the development process as land is graded and wetlands are filled. Man-made channels and stormwater systems are designed to transport runoff to the stream more "efficiently" and result in more water reaching the stream in a shorter time period and at a higher velocity.

The primary effects of development on hydrology is a decrease in infiltration and a corresponding increase in surface runoff. Leopold (1973) found that the number of floods exceeding channel capacity increased from an average of two per year to more than ten per year following urbanization. Hollis (1975) found that peak storm flows positively increased with greater amounts of impervious surfaces. Almost 20 years later, Booth (1991) found a two- to three-fold increase in peak flows in watersheds with 10-20 percent imperviousness (based on effective impervious area).

In addition, watershed development activities also increase the frequency of bank-full and smaller events (Leopold, 1973). Bank-full events are defined as those that completely fill the stream channel but do not overtop its banks. A greater number of bank-full flows in the disturbance regime of a stream normally translates to more substrate scour, greater bank erosion, and more frequent instream structural realignment (Leopold, 1968).

The increase in impervious surfaces created by construction of roads, parking-lots, and roof-tops is the most significant driver of increased runoff (Schueler, 1994). All these elements result in a dramatic increase in the volume and rate at which water is delivered to the stream system. This increase in discharge affects the stream geomorphology. In developing watersheds, the road network can significantly increase the effective length (direct hydraulic connection) of the stream channel network and strongly influence watershed hydrology.

Urbanization Impacts to Stream Geomorphology

Hydrological impacts cause channel and bed erosion and tend to increase cross-section areas. This resulted in channel-altering flows, reduced in-channel roughness and channel-bank resistance, and increased sediment load. These changes in morphology were shown to be correlated to a threshold of about 10% imperviousness.

The channel shape of most Puget Sound Lowland region streams is sinuous, predictable sequence of pools, riffles and bars in channel (Montgomery and Buffington, 1997). This creates a stream reach with variability in bedforms and habitats; loss in variability (or complexity), such as decrease in frequency of these riffles or a more homogeneous bed, could likely be caused by urbanization impacts. The frequency and location of different types of channel units within a reach can be affected by a variety of disturbances, including anthropogenic disturbances that remove structural roughness elements such as large woody debris (LWD) (Lisle 1987) or impede the ability of a stream to interact naturally with its adjacent riparian zone (May, 1996).

Most scientists agree that stream ecosystems are dynamic in nature but that there is a natural tendency toward equilibrium through adjustments in channel morphologic characteristics. Leopold and others suggest that a stream continuously adjusts its depth, width, velocity, roughness and water surface slope in order to establish an equilibrium between discharge and sediment load (Dunne and Leopold et al., 1978. These variables are mutually interdependent, meaning that a change in one parameter will result in an adjustment of the others. The increased amount and rate of discharge in an urbanized area causes an increase in shear stress (λRS), which is defined as force per unit area (of the stream flow) acting parallel to the stream bed (Maryland Department of Natural Resources, 2004). In many stream channels, this results in channel widening and/or channel deepening to accommodate the increase in bankfull or dominant discharges. In this context, the channel may merely change from one bankfull condition to another as a result of increases in runoff and bankfull discharge. This does not seem to be the effect in all or perhaps most urban areas. Instead, the new flow regime may cause significant channel erosion that changes not only the channel size, but also its morphology, flow resistance and habitat function. This is represented by such factors as loss of aquatic habitat, i.e. riffle pool systems, reduced organic debris, and minimal periphyton (biological growth) on streambed cobbles.

Another impact due to urbanization involves the elevation of the streambed. In general, the sediment carrying capacity of streams is permanently increased, and therefore causes the channel bottom to degrade, resulting in net removal of material from the bed (Hammer, 1972). This significantly decreases the gradient of the streambed, which shifts the distribution of gradients within watersheds or concentrates changes in elevation at stream crossings, such as bridges. It is important to note that the elevation change as a result of urbanization is not uniform throughout the channel.

The changes in bed substrate mobility and the decrease in channel gradients may lead to a decrease in stream morphology complexity, primarily represented by the destruction of riffle and pool systems, which serve as primary aquatic habitat. The result is a stream channel that is too wide, too shallow, and too homogeneous to support fish populations.

Changes in basin hydrologic regime result in long-term and extensive changes in stream channel morphological characteristics. In general, streams tend to develop a physical structure that depends on the frequency and magnitude of discharge events. Urbanization impacts may cause significant changes in physical structure, such as channel enlargement, accelerated streambank erosion, an increase in stream valley side-slope mass-wasting events, elevated downstream sediment loading, and degradation of instream habitat.

As was discussed previously, streamflows in the Puget Sound are driven by storm precipitation and runoff input. Therefore, the degree of change in channel morphologic features is, in part, a function of the level of urbanization within the basin (Schueler, 1994). The increase in total volume of surface runoff and the concentration of stormwater into surface channels instead of infiltration and subsurface flow combine to change the morphological character of the stream channel. The response of a stream channel and the extent of the change will also depend on the physical characteristics of the stream channel (basin size, stream gradient, sinuosity, etc.). In the Puget Sound, many streams are low gradient, debris-regulated, gravel-bed systems with irregularly spaced pools and riffles, while others are dominated by fluvial processes which tend to have regularly spaced morphological features (May, 1996). Morphological changes, in turn, have a feedback loop with hydrologic response as the stream continues to evolve toward a dynamic equilibrium condition.

The normal mode of stream channel enlargement is quasi-equilibrium expansion where increases in discharge magnitude and duration result in proportional increases in channel width and depth (Leopold, 1968; Hammer, 1972). Channel widening to accommodate increased flows is primarily accomplished by lateral erosion of stream banks. The key flow event in the channel enlargement process is the bankfull flow. For watersheds affected by urbanization, stream channels tend to grow by an amount sufficient to maintain a similar quasi-equilibrium state under the altered flow regime. However, the increased magnitude and frequency of bankfull flows results in continued channel enlargement. Hammer (1972) found that the influence of urban development and impervious area on channel enlargement is related to basin topography (slope), type of impervious development, age of the development, actual location of the impervious development within the watershed, and to the man-made drainage alterations present.

Channel expansion not only results in streambank erosion along with downstream sedimentation, it also encroaches on the stream's riparian forest and hillslopes. The channel may equilibrate with the increased flows within a period of a few years, but the hillslope failures and local streambank erosion resulting from increased bank undercutting can continue for decades (Booth, 1990). Hammer (1972) found that established (at build-out) residential areas over 30 years old showed little channel widening over time.

Bedload transport and streambed scour are important morphological processes in streams of the PSL. These processes are a natural part of the stream systems of the PNW. Fluvial transport of sediment delivered to the stream channel by hillslope processes is a necessary part of the morphologic functioning of all streams and rivers. Localized degradation (scour) and aggradation (fill) occur throughout a stream system, generally maintained in a dynamic equilibrium condition by hydrologic forces. Stream power is defined as the power available to transport sediment load (including suspended sediment and bedload). Stream power is proportional to stream discharge and slope. Higher peak flows and more frequent high flow events brought on by urbanization normally result in greater power available for sediment transport and can disrupt the dynamic equilibrium of the stream channel.

Large organic debris also provides significant resistance to flow, traps sediment, and dissipates stream power (May, 1996). In addition to stream power, sediment transport or flow competence can be represented by the basal shear stress, which is proportional to the flow depth and the slope. Basal shear stress at bankfull conditions is referred to as bankfull shear stress. Bankfull shear stress will be used as the preferred term throughout this thesis. As with stream power, channel gradient (or slope) is a major factor in the energy equation. The resistance to sediment transport is defined as the critical shear stress or the shear stress required to initiate motion. Critical shear stress is highly dependent on the median sediment particle size (May, 1996).

Streambank erosion is driven by the same factors as streambed scour; discharge, shear stress, channel gradient, and substrata. Factors influencing streambank erosion potential include frequent high-flow events and stormwater runoff, constrained channel widths, lack of floodplain area to dissipate flows, loss of riparian vegetation and root systems to hold soil in place, and the loss of in-channel structure and streambank protection (organic debris). Most sediment input to streams in the PNW comes from streambank erosion and mass-wasting events (Booth, 1990). This is especially true of urbanized basins where much of the discharge originates from relatively low-sediment paved surfaces or emerges sediment-free from stormwater outfalls.

The amount of sediment deposited in urban stream channels is often greater than what the natural stream channel can transport through the system. Flows greater than 60% of bankfull tend to mobilize streambed material depending on substrata size and composition. Much of this sediment may remain in temporary storage within the channel in the form of gravel bars (coarse sediment) or as silt deposits (fine sediment). Excess fine sediment along with higher flows can also cause the streambed to become embedded, further reducing benthic habitat and spawning area.

While urbanization often results in an increase in sediment load during the construction phase (Booth, 1990), there can actually be a reduction in watershed-wide sediment yields in more established urban areas (Arnold et al, 1982), resulting in streambed scouring and incision. The combination of atypically large sediment loads and stream channel enlargement also has a profound effect on the longitudinal structure of urban streams. The sequence of pools and riffles that is characteristic of natural streams is degraded into a uniform-depth, glide-dominant channel as the gradient and dimensions of the stream adjust to accommodate the more frequent, higher flows (Lisle, 1979).

The loss of pool and riffle structure in urban streams significantly reduces the quantity, quality, and diversity of instream habitat. This loss of channel complexity (in the way of pool and riffle structure) is a major effect of the morphological changes resulting from urbanization and has had a critical effect on the populations of coho salmon and other salmonids in urban streams (May, 1996)

Study Sites and Methods

Study Area

I conducted this study on six streams in the Puget Sound Lowland region of western Washington. The region, at 35,000 square kilometers, encompasses the entire Puget Sound Basin and is bounded by the Cascade and Olympic mountains. The predominant geology of the region is a result of repeated glaciation, creating similar geomorphologic stream systems. The region receives approximately 1,000 mm (~39in) of precipitation annually that falls at low intensities. Most occurs between November and April as rain and occasional snow in higher altitudes (Konrad and Booth, 2002). The average rainstorm during this time is approximately 18mm (0.5 inches) in 24 hours, although low-intensity, long-duration (multi-day) storms are common (May, 1996). Typically, little precipitation falls between July and September.

Konrad and Booth (2002) describe streamflow in this region to be produced by runoff during frequent (low intensity) rainstorms and groundwater discharge from shallow aquifers. The largest runoff peaks are produced by multi-day storms, which continue long enough to raise hillslope ground water tables and thereby expand the area of runoff-producing saturated ground surrounding streams and swales.

About 70 percent of the population in Washington lives in the Puget Sound region (Ebbert et al., 2000). Though most of the upper basin is forested (foothills and mountains), the Lowland region has a range of land cover, from slightly suburban to highly urban, with most of the population concentrating in the urban centers or on the urban fringes increasing urban sprawl (Ebbert et al., 2000. The two counties in which the six stream sites are located – King and Snohomish – have grown considerably from 1980 to 2000, with King County's population growing approximately 27% and Snohomish's about 44% (Washington State Dept of Finance). As mentioned before, the Puget Sound Basin streams and their in-stream habitat have been greatly affected by this development. Thus, this region proves to be appropriate to investigate impacts to stream channels over a range of urbanization.

Site Selection Criteria

The six sites chosen for this study, located in King and Snohomish Counties, were selected to examine the effects of urbanization on stream channel morphology. As described, because of their shared location, the stream sites have similarities in climate, geology and topography.

The long-term geologic and geomorphic structure of a drainage basin can be viewed as a template, which structures the complex response of the stream system (May, 1996). Thus, this helps to create their natural variability.

One of the main points of this study is to quantify the amount of variation present (or not) in the stream sites. It has been shown that the hydrologic and geomorphic effects of urban development are not easily evaluated because variability in streamflow patterns, over time ranging from hours to decades, is not always a consequence of anthropogenic activities (Konrad and Booth, 2002). Thus, in order to focus on geomorphic changes caused by urbanization, it was necessary to minimize the probability of measuring changes simply caused by natural variability in stream dynamics. Strict criteria were established to minimize this variability so that comparisons could be made between chosen stream sites. The criteria used included (Table 1):

Criteria	Characteristic	Data Source
Drainage Area	Approximately 10-40 km^2	Previous work (Booth, Konrad, May)
Geology	Similar history	King County/City of Seattle geologic maps (Galster, et al); (Booth, personal communication, 2001)
Slope	Less than or equal to 3% *(based on Montgomery, Booth)*	USGS topo maps; previous work (Konrad, May)
Urbanization	Range of less than 5% to greater than 40%	Previous work (Booth, Konrad, May)
Location of Reach	Natural channel; no bridge crossings, man-made restoration structures in reach or near upstream of the reach; if so, site must be located approximately 50-100m downstream of structure or bridge. *(based on C. Konrad)*	Site visits; Thomas Brothers Maps (2001)
Banks	No severe erosion; well-vegetated banks	Site visits

Table 1 . Selection site criteria.

1) Drainage Area: Drainage areas of the study stream sites were limited to a range of approx 10 to 40 km^2. Drainage areas from other work (Booth, 1990; Konrad, 2002) were used to guide the selection of possible site locations.
2) Geology: Since the predominant Puget Sound geology was formed under same conditions, the streams within the Lowland region were determined to have similar geology, thus having similar hydrology with respect to geologic effects. However, attempts were made to not choose sites in or affected by outwash areas.
3) Slope and Channel Type: According to Montgomery (1997), streams in the Puget Sound Lowland region typically have riffle-pool systems, alluvial valleys, and low gradient, approximately less than three percent. This three percent limit includes both "free" pool-riffle channels, where morphology is formed from inertial characteristics of the water moving in a meandering channel and 'forced'

pool-riffle channels, which are generally formed by obstructions, usually large woody debris (LWD). In this case, removal of LWD would cause the channel to lose its riffle-pool systems, and the type of stream from change from a riffle-pool system to another (Booth, Montgomery, and Bethel, 1997). Booth et al. (1997) explained that channel types, in addition to geological context and the nature of bank-forming materials, help to determine how a watershed will respond to watershed changes, in this case urbanization.

4) Range of Urbanization: To investigate the impacts of urbanization on streams, it was necessary to consider streams that had watersheds with varying degrees of urbanized land use. This was done to test the hypothesis that streams become more homogeneous geomorphologically as urbanization increases. Past measures of imperviousness were used as guidance in choosing possible study sites. United States Geological Survey (USGS) 7.5" quads were also examined to gain a general understanding of levels of development in the various watersheds of the Puget Sound Lowland region. Methods to measure urbanization in those sites chosen for the study will be explained in a following section.
5) Non-Restored Reaches: Study reaches chosen for the study were to be as natural as possible. This meant that the reaches had yet gone through a restoration process, and no structures had been placed in the channel. In addition, no bridges were located within a stream reach, and if one was located upstream of the reach, the reach was set a distance of at least 50 to 100m downstream of the bridge to minimize impact from it (Konrad, 2000). Because no database exists of stream

restoration projects, it was not possible to be certain that no structures were in place upstream of the reaches.

6) Vegetated Banks: To avoid channels that were already severely eroded or void of riparian buffers, only stream reaches with banks of shrub/tree vegetation were chosen. However, a few cross-sections within some study reaches had vegetated banks with grass and little shrubbery, though the majority of the reach did not. No reaches with bare banks were chosen.

7) Access to Study Sites: Because of lack of time and resources, only reaches that were relatively simple to access from a street or bridge crossing were chosen.

I made the best attempts to choose streams that fit this set of study criteria. This involved much time as it was difficult to find sites that fit all criteria.
I visited approximately twelve additional sites that that were not used, because they fell short of one or more criteria. This was especially true with streams on either end of the urbanization spectrum. Most streams located in the more rural areas have very steep banks or are on private property, which are difficult to access or where access is not allowed, whereas many heavily impacted streams have already been restored in some way so that natural stream processes are difficult to measure. In light of this, it is believed that the six streams chosen are a good representation of those located in the Puget Sound Lowland region that have been affected by varying degrees of development.

In addition, it was expected that engineered structures for stream restoration would be one of the main obstacles for choosing stream sites. However, it was found that other human-related obstacles were also present. For example, the middle of the Covington Creek watershed (the least urbanized and located in a rural area of King County) had many houses with backyards to the creek, where pipes had been installed between the yard and creek. It is unknown at this time what the landowners were doing with those pipe structures, although it is assumed that this may cause additional impact to the natural streamflow regime.

Study Sites

I selected six stream sites that fit the criteria as closely as possible (Table 2). The study watersheds, located in two different counties of the Puget Sound Lowland region, were chosen to cover a range of urbanization and types of development in order to explore differences in stream geomorphology according to this range. Because of geology, climate, watershed size, slope, and channel type are all similar, observed differences in stream complexity can be attributed to differences in urbanization.

Covington Creek, with the second largest drainage area at 48.4km^2 was chosen to be the reference, or least urbanized, stream. This site was originally chosen as reference site based on personal communication and past work (Booth, 2001); however, the imperviousness calculated (in Arcview GIS) resulted in a value of 16.4%. Although it was a higher amount of imperviousness, of all the sites, it does have the least amount of impervious area and the most forested area, with wetlands and ephemeral streams in its headwaters. (This may change in the next few years as it is beginning to be subject to suburban sprawl). In addition, it is the only stream in the unincorporated King county area that is outside of the urban growth boundary. This study watershed is also different from others in that it has glacial outwash soil in the upper watershed. The site chosen however, is a distance downstream from the outwash and is not significantly affected by it (Booth, personal communication, 2001).

The May Creek watershed encompasses 45.1km^2 and is the second least impervious after Covington Creek, at 22.3%. May's headwater streams flow from steep, forested, fairly erosive ravines into the upper portion of the watershed that is characterized by less dense residential and agricultural development. The Creek then flows into the lower portion of the watershed, where the study reach is located, then into Lake Washington and then the Puget Sound. This portion is inside the Urban Growth Boundary and is fairly dense urban residential development (King County, 2004). However, where the study reach is located, May Creek has forested and shrubby riparian buffers.

Cottage Lake, Swamp and North Creeks are adjacent watersheds that flow into the Sammamish River, which flows into Lake Washington and ultimately into the Puget Sound. Approximately 95% of the combined area of the three watersheds is within Snohomish County, with the lower portion of each sub-basin located in King County (May, 1996). Cottage Lake is the smallest of the watersheds with a drainage area of 30.7km^2. The imperviousness measurement of the watershed is 25.5%, with its headwaters undeveloped and located in the Crystal Lake wetlands. The stream then flows to Cottage Lake, which originally was a headwater wetland lake and now has been designed for development and recreation. The study reach is located below Cottage Lake. Though private yards abut the Creek at this site, the study reach is well vegetated by deciduous trees and shrubs, and the Creek is undeveloped immediately upstream of the study site.

Swamp Creek has the largest drainage area at 50.8km^2 and has 43.3% imperviousness. Swamp originates in the Paine Field airport, an area that was once dominated by extensive wetlands. The upper reaches of the Creek still have some large good-quality wetlands, as well as one of the largest populations of freshwater mussels found in the Puget Sound Lowland region (King County, 2004). The study reach is located between private backyards and undeveloped fields, mostly vegetated by trees, shrubs, and lawn.

Having a similar drainage to Cottage Lake, North Creek's watershed area is 32.0km^2. North Creek is the second most urbanized watershed with 46.5% imperviousness. In addition, the headwaters are highly urbanized as they are dominated by commercial and multi-family residential development, including a large shopping center. The upper-middle mainstem of North Creek includes the City of Mill Creek, a rapidly growing community with several new large-lot developments. The study reach site is located downstream of these developments, however its immediate area is an older development with public government buildings. Its banks are shrubby with some mature deciduous trees and conifers.

The most urbanized watershed of all study sites is Miller Creek, with 56.5% imperviousness and a watershed area of 20.6km^2. The Creek's headwaters receive drainage from the Seattle Airport, Burien Lake, and the city of Burien; however, some small bogs and wetland lakes do still remain (May, 1996). A sewage treatment plan is also located in the middle of the watershed and upstream of the site, though it does not discharge into the creek. Its streamside access road does appear to affect the creek. The study reach is in a steep-walled ravine with a mostly intact riparian corridor of mixed mature trees (May, 1996).

Stream Sites	County Location	USGS 7.5" Quadrangle	Drainage Area (km^2)	Gradient (%)	Contributing Tributaries and Lakes	Headwaters	Other Habitat, Riparian Area	Major Land Use
Covington Creek	King	Black Diamond	48.403	0.0009 (.09)	Lake Sawyer and Ravensdale Lake	Wetlands, second-growth forest and ephemeral streams	Riparian wetlands, especially above Lake Sawyer; many pocket wetlands; overlying consolidated glacial till soils, rainfall in upper watershed quickly absorbed by outwash soil, , high groundwater table (May, 1996).	Rural, low residential
May Creek	King	Bellevue South	45.065	0.0094 (.94)	Honey Creek, Boren Creek and the North, East, and South Forks of May Creek; Lake Kathleen in southeast of watershed and Lake Boren in northwest of watershed	Come off steep, forested, fairly erosive ravines (Kerwin 2002). Includes significant portion of undeveloped parkland.	400 acres of wetlands (Kerwin, 2002)	Mostly rural upstream; mid to dense residential
Cottage Lake Creek	King	Maltby and Kirkland	30.729	0.004 (.40)	Daniels Creek, Crystal Lake, and Cottage Lake	Crystal Lake wetlands.		Low to mid residential
Swamp Creek	Snohomish	Edmonds East	50.827	0.0007 (.07)	The drainage basin includes Scriber Lake, Martha Lake, and Lake Stickney	Paine Field airport, once dominated by extensive wetlands.	Some large good-quality wetlands, as well as one of the largest populations of freshwater mussels found in the Puget Sound Lowland region (King County)	Mid-Dense residential
North Creek	Snohomish	Bothell	31.957	0.002 (.20)	Silver Lake, Ruggs Lake and Thomas Lake.	Dominated by commercial and multi-family residential development.	Site vegetated by some mature deciduous trees and conifers.	Mid to dense residential
Miller Creek	King	Des Moines	20.608	0.0001 (.01)	Arbor, Tubb and Burien Lakes	Honey Creek, Boren Creek and the North, East, and South Forks of May Creek; Lake Kathleen in southeast of watershed and Lake Boren in northwest of watershed	Some small bogs and wetland lakes; site: steep-walled ravine with a mostly intact riparian corridor of mixed mature trees	Dense residential; Seattle airport

Table 2 – Watershed site characteristics.

Field Collection Methods

The field methods employed were mainly customized for this study, although a handful of methods were borrowed and other techniques consulted (Ramos, 1996).

A reach was chosen in each stream according to the methodology (see below), resulting in the selection of alluvial reaches with reasonable access. Reaches were located with a Garmin 12XL global positioning system (GPS) unit (approximately +/- 10m error) and later mapped using Arcview Geographical Information System (GIS) to determine watershed boundaries of the sites. Most measurements taken were quantitative measures of the stream bed and bank. Qualitative measurements included observations of channel morphology, riparian areas and stream habitat (to describe channel morphology, dimensions and structure).

The goal of the field collection was to capture the variation of characteristics from one place of measurement to the next within each study reach through repeated measurements of basic channel morphology. The objective of this was to capture the heterogeneity of the stream channel and bed and make comparisons between the six sites, as well as have adequate data for reach-averaged characteristics.

Site and Reach Selection

As mentioned, my intent was to choose streams that fit the set of criteria as much as possible, in order to quantify the variability of a stream within each reach and also compare the variability among the streams according to urbanization.

The first step was to determine which sites used in past studies fit the criteria chosen for this study. To do this, I gathered information from various sources: past researchers (Booth, 2001; Konrad, 2000), and King County and Snohomish County

Departments of Natural Resources. Based on the information gathered, a list of 20 possible sites was compiled. I visited all sites and chose six that fit the strict selection criteria. Additional sites were difficult to find, as many did not fit all or most of the criteria.

The second step was to choose the reach for each stream in which to conduct measurements. To choose the reach, I considered the difficulty of access to the reach and feasibility of carrying out the measurements. I also qualitatively assessed the longitudinal reaches of each stream – if the banks showed signs of human-induced impact, that stream was not chosen. Finally, reaches were chosen according to fit of criteria, not according to presence of riffle-pool systems, or other channel unit (certain classified feature or channel type described by certain characteristics).

The third step was to determine the length of the study reach. The following procedure was carried out at each site. A meter tape was used to measure the general bankfull width along the reach, and the reach length was determined to be 10 to 14 times the bankfull width. Bankfull width describes the width of the channel in which flow just fills the channel without overtopping the banks; considered approximately a 1.5-2.0 year event (Maryland DNR, 2004). This standard was used, because riffle-pool systems (the stream type in this study) are spaced every five to seven times the bankfull channel width longitudinally along the reach (Lisle, 1982). Thus, to capture at least one riffle-pool system, a reach length of 10 to 14 times the bankfull width was used. Thus, the length of the reach at each site varies according to that reach's average channel width. The range of reach lengths studied is from 55.1m to 116.7.

Cross-Channel Measurements

At each reach, the spacing distance of the cross sections to be measured was determined by dividing the reach length by 20. Montgomery and Buffington (1997) recommend studying channel reaches of at least 10-20 channel widths to relate stream morphology to channel processes and response potential. As this study seeks to describe channel morphology and complexity, carrying out 20 cross sections at each reach should suffice.

Once spacing was determined at each reach, each cross-section was set-up at channel bankfull by using rebar at both left and right banks and tying carpenter's string between them. These cross-sections were marked with a flag above the bank in order to locate them if necessary throughout the study. Channel bankfull was determined by consideration of presence or absence of perennial vegetation, topographic breaks in the bank, and any change in sediment size or texture (Dunne and Leopold, 1978). A string level was used to adjust the string as a reference from which to take measurements. Channel dimensions were determined by measuring bankfull width and bankfull depth. Bed depth was measured from left (if looking downstream) to right bank at least every 0.5 meters using a marked wading rod. The wading rod was placed at the top of the bed, and the depth was measured from that point to where it touched the string (while not touching the string so that it stayed level). Additional measurements were made in areas of observed changes in bed heterogeneity. Bankfull cross-sectional area (area of a cross-section of a channel at bankfull stage), wetted perimeter (perimeter in channel touching streamflow), and hydraulic radius (cross-section area/wetted perimeter) were derived from the measured channel dimensions.

Substrate measurements were also taken at each cross section of each reach. The Wolman pebble count method was performed to measure bed substrate using a ruler marked into grain size ranges (Wolman, 1954). Different workers carried out this method at the six study reaches; however, only one worker carried this out at each site. Past work by Brush (1961) shows that statistically there was no significant difference between results obtained by different operators making pebble counts, nor within the same traverses, but differences between traverses were significant at the 1% level (Dunne and Leopold, 1978). On the basis of his findings, he suggested using 60 pebbles as the smallest number necessary to give reproducible results. For this study, 100 pebbles were used at each cross section, and error is therefore assumed to be minimal.

In addition, the riparian areas along the reach lengths were visually observed to gather a general idea of the amount and type of vegetation present. It was noted if the bank was vegetated, and what its general type was, such as tree, shrub, vines, or grass.

Longitudinal Measurements

Elevation at the bank's edge and at the thalweg (primary path of stream flow within a channel) was measured longitudinally along each reach. A hand level was used to take the depth measurements from the downstream to the upstream end of the reach. Measurements were taken at observed points of gradient (or slope) or channel changes throughout the reach. These measurements, along with depth measurements taken at the cross-sections, were used to determine reach gradients of the sites by creating slope profiles, which are shown in the results section.

Spatial Analysis Methods

This section describes the types of data used in the spatial analysis to calculate land cover of the study watersheds. My intent was to use spatial data to calculate the drainage areas and urban land cover areas for all six stream sites. These measurements were then used to calculate the land cover make-up and imperviousness percentages of each of the watersheds. All processing of spatial data was completed within ArcView 3.2 software (ESRI, Redlands, CA). All data are projected in UTM Zone 10 (NAD 27). Following is a brief description of each data type used for these calculations.

Data sources

1) Reach locations: Each site was located using a Garmin 12XL GPS unit. The coordinates of each site's location were entered manually and a point shapefile was created. The error of these GPS points is approximately +/- 10m.
2) Watershed Boundaries: Clipped Digital Raster Graphics (DRG) were used to manually delineate the drainage (or watershed) boundaries by following the topographic lines on the maps. A DRG is a scanned image of a U.S. Geological Survey (USGS) standard 7.5" series topographic map. Clipped DRGs do not include map collar information (white trim around map with information about origination, orientation, and scale) and are easier to overlay. The horizontal positional accuracy and datum of the DRG matches the accuracy and datum of the source map. The map is scanned at a minimum resolution of 250 dots per inch (http://topomaps.usgs.gov/drg/). I used a 10m, 1:24,000 digital elevation model (DEM) as guidance in determining topographic breaks and depressions to more accurately outline the study watersheds. The DRGs, DEM and their metadata are

available online at the Washington State Geospatial Data Archive (http://wagda.lib.washington.edu/data/washdata.html).

3) Stream Network: The hydrography, or stream network, data was used as base data to outline watershed boundaries. It was available online from the Washington State Department of Natural Resources at http://www.dnr.wa.gov/dataandmaps/.

4) Land Cover: To characterize the land cover of the study watersheds, a land cover classification of the Landsat 1998 image was used. This classification, available online, was used to calculate the land cover make-up of each watershed (http://depts.washington.edu/cwws/Research/Projects/landsat.html). The 30-m classified image is divided into seven categories as shown in Table 3. Three of these categories are considered urban under this classification and include forested urban, grassy urban, and paved urban (Table 3). The authors checked classification against orthophotos to determine how 'correctly' the procedure identified the different categories. The analysis produced an overall accuracy of 77 percent, with the worst performance for the two classes with the greatest mixture of land covers: *grassy urban* (most pixels were "more urban" than anticipated) and *forested urban* (the misclassified pixels were both more and less urban than expected) (Table 3) (Hill et al., 2000). Although the classification discriminates well between developed and undeveloped land uses, the true land cover for individual pixels in a same class can vary widely and lead to some uncertainty (Hill et al., 2000). However, the authors did determine the minimum number of pixels (and corresponding land area) required to limit errors in total

impervious-area percentages to one percentage point in each of the classes. Hill et. al (2000) found that as a general rule, low-development watersheds should be a few hundred acres for estimates of total imperviousness within a few percent, whereas more urban areas require areas of one-half to one square mile for equally reliable results. In addition, the more urban areas should be evaluated over areas of one to two square miles (or more). The watershed areas of the sites in this study are well over this amount.

EXPECTED (i.e. pixels as classified)	OBSERVED (from orthophotos):	forested urban	grassy urban	paved urban	grass/ shrub/ crops	water	bare soil	forested	**Row Total**	Consumer's accuracy:
	forested urban	27	5	4	9	0	0	5	**50**	54%
	grassy urban	0	9	35	6	0	0	0	**50**	18%
	paved urban	0	0	47	1	0	0	2	**50**	94%
	grass/shrub/ crops	0	0	0	49	0	0	1	**50**	98%
	water	0	0	0	0	50	0	0	**50**	100%
	bare soil	0	1	7	3	0	39	0	**50**	78%
	forested	0	0	0	1	0	0	49	**50**	98%
	Column Total	**27**	**15**	**93**	**69**	**50**	**39**	**57**	**350**	
Producer's accuracy:		100%	60%	51%	71%	100%	100%	86%		**77% = overall accuracy rate**

Table 3. Urban land cover classification by Hill et al. (2000)

Land Cover Measurement

In order to calculate land cover for the study watersheds, the watersheds were first manually delineated using DRGs. Although the typical method for watershed delineation is using hydrologic functions of Arcview software using a DEM, this sometimes leads to cell resolution error and was determined that manual delineation would be adequate (Winchester, 2003). Using the GPS points in Arcview as the downstream watershed boundaries (with the DEM as additional guidance), the six watersheds were delineated. Points were adjusted according to the stream network on the DRG if there was GPS-related error (+/- 10m).

These delineations were overlayed on the land cover classification in order to calculate the amount of each cover type within the watersheds. The following procedure was carried for each of the six study watersheds. First, the number of pixels were determined for each cover type within the watershed. The 30-meter grid meant that area of each pixel was 900m^2. This meant that the area of each of these cover types could be determined using the number of pixels counted. The result was an area for each land cover type of each watershed, allowing for these to be totaled for the drainage area of each of the sites (Table 4).

Watershed	Paved Urban	Forested Urban	Grass/Shrub Urban	Bare Earth	Forested	Grass/Shrubs/ Crops	Water	TOTAL (km^2)
Covington	1.178	8.864	4.144	0.408	29.876	2.861	1.073	48.403
May	1.076	8.510	7.413	0.331	24.491	3.119	0.124	45.065
Cottage Lake	0.584	12.425	3.274	0.150	11.975	1.949	0.372	30.729
Swamp	6.386	14.115	13.605	0.707	11.441	4.296	0.277	50.827
North	3.934	9.233	10.076	0.266	5.550	2.489	0.409	31.957
Miller	3.298	4.372	9.040	0.261	2.052	1.446	0.140	20.608

Table 4. Calculated land cover type areas by study site.

Because Hill's analysis was conducted at a much finer scale (30-m pixels) and detects only land-cover differences, total imperviousness (urban land cover) can be calculated. Land-use categories, and thus EIA, might be inferred from larger clusters and patterns of individual pixels, but this lies outside the scope of this present effort.

The most common measure of imperviousness is percent total impervious area (%TIA) and is based on assigning a regionally-accepted, specific percent imperviousness to the various categories of land use found within each basin (Schueler, 1994; Olthof, 1995; May, 1996; Hill et. al, 2000; McBride, 2001). I decided to use this method to characterize the urbanization in these watersheds. Using the imperviousness values for each of the land cover types determined by (Table 5) (Hill et. al (2000), the imperviousness of each land cover type was determined, in addition to the total percent imperviousness. Error associated with this land cover measurement procedure include that error related to manually delineating the watersheds using the DRGs. Delineations may be over- or under-estimating watershed areas, because of the quality of the DRGs. Thus, the percent imperviousness calculation may be have resulted higher or lower than the actual value. However, one worker carried out all delineations, it is assumed that it is appropriate to make comparisons between study sites. At the same time, although GIS data serve as models of features of the true landscape, accuracy is always limited by spatial errors, data quality, map scale and other factors (McBride, 2001).

Categories from Classified Image (Hill et. al)	Impervious Area % (Hill et. al)
"Undeveloped"	
Open Water	0
Forested	3
“Developed"	
Grassy/Shrubby Vegetation	5
Bare Earth	98
Forested Urban	38
Grassy Urban	74
Intense (Paved) Urban	92

Table 5. Imperviousness values for land cover types (Hill et al, 2000).

<u>Data Analysis Methods</u>

The data analyzed for this study was carried out in various phases. These phases included: 1) watershed and land use characterization; 2) analyzing geomorphic data collected in the field; 3) studying within-stream variation of all sites; 4) comparing the morphology of reach-averaged variables and single cross-section measurements; 5) comparing shear stress of reach-averaged variables and single cross-section measurements; and 6) analysis of complexity of the sites in relationship to urbanization.

Land cover calculations

First, I assessed the land cover distributions of the study watersheds that were determined using the spatial analysis methods. I calculated the percentages of each land cover type in each watershed and also calculated the percentage of imperviousness by type and then the total by watershed. Next, I made comparisons between land cover and imperviousness values to determine if the relationship was appropriate.

In-Stream Complexity

All data collected in the field was gathered into a spreadsheet and organized by stream reach, and additional geomorphic variables were calculated using the raw data. To study the variation within each reach, values of morphology characteristics were plotted along the downstream direction of the reach. This was done so that the complexity, or variation, of geomorphic characteristics could be assessed from point to point of measurement. The characteristics plotted include the following: channel width; channel depth;

width/depth ratio; cross-sectional area; grain sizes (D_{16}, D_{50}, and D_{84}); depth/D_{84} and depth/D_{50} (ratios used to describe relative submergence/ roughness); D_{84}/D_{50} (used to describe substrate heterogeneity); and (D_{84}-D_{16}/2) (used to describe bed sorting). All characteristics (except those measured in the field – width, depth, and grain size) are derived from raw data collected in this study. As these field collection methods have been used by others (Ramos, 1996), they are assumed to be adequate to describe the geomorphic qualities of the creek. The standard deviation (SD) for each variable by stream was also calculated to determine the spread of values about the mean and compare this spread among sites.

Comparison of Averaged Morphological Variables to Values of a Single Cross-Section of Each Reach

Streams with riffle-pool systems were chosen for this study. Some practitioners investigate stream channels by measuring morphology within or downstream of channel units. Riffle-pool systems are a common channel unit in the Puget Sound Lowland region, especially in streams with the characteristics of the study sites (Montgomery and Buffington, 1997). According to this method, however, carrying out only select cross-sections at certain channel units may affect the results of the geomorphic assessment of the stream. This portion of the study investigates if measurements taken within a single cross-section (as in Rosgen (1996), Harrelson et al (1994) may adequately describe the overall reach morphology. Thus, to capture adequate detail of channel morphology, a high number (<= 20) of cross-sections were used in this study for comparison to this other method.

After cross-section measurements were taken at each site (field collection methods), the average (or mean) of each variable under investigation was calculated from the data for each stream. Then, the data of each site was grouped by type (i.e., the average widths of each stream were grouped with all widths). To select a single cross-section as comparison, longitudinal profiles were inspected, and the most downstream riffle within each study reach was determined. At that point, the cross-section immediately downstream of the riffle was chosen for this comparison to the reach measurements. The variables characterizing this specific cross-section were gathered from the same field data. Then comparisons of morphology variables were made between the means of the reaches and the single cross-section measurements.

In addition, the standard error of the mean was determined for each variable (based on one standard deviation from the mean). The standard error was used to calculate the 95% confidence limits for each variable mean. The limits are represented on the comparison plots as error bars for each variable and reach.

Comparison of Averaged and Single Cross-Section Shear Stress of Each Reach

Similar to the comparisons of morphology, the reach-averaged variables and the single cross-section measurements were compared to the shear stress ratios of the study sites. The shear stress ratio was determined by first calculating bankfull shear stress and critical shear stress, and then dividing the first with the latter. Bankfull shear stress can be described by the force of the stream flow acting on the stream bed, with the force including both drag and hydraulic lift. It is calculated using the following equation:

$$\tau = \rho g S d, \quad (1)$$

with $\rho g = \psi_s$=specific weight, S=slope, and d=depth. The bankfull shear stress can be calculated by both mean depth and mean hydraulic radius. Generally, depth and hydraulic radius are similar in wide channels and can substituted by the other. Most reaches in the Puget Sound region, however, are narrow, and the depth and hydraulic radius are significantly different from each other. For this analysis, hydraulic radius is considered more appropriate because of the channel size and is therefore used in the bankfull shear stress calculations (Prestegaard, 2003).

If shear stress reaches a 'critical' level, the bed becomes mobile, and bed substrate is moved downstream with the flow. This stress is the critical shear stress and describes the stress at which the incipient motion of a certain grain size begins (Buffington and Montgomery, 1992). Critical shear stress is calculated using the Shields Parameter, or 'dimensionless critical shear stress', equation:

$$\tau_{c50} = \tau_{*c50} * (\psi_s - \psi) * (D_{50}) \quad (2)$$

with τ_{c50}=bankfull shear stress, τ^*_{c50}=Shields Parameter; ψ_s=specific weight of sediment; $\psi_=$specific weight of water; and D_{50}=median substrate size. τ^*_{c50}, called the 'dimensionless critical shear stress,' represents the ratio of applied shear stress to the submerged weight of a particle *at initiation of particle movement* (this makes it "critical") for a grain of diameter D (Buffington and Montgomery, 1997). For this study, since it is difficult to measure, 0.5 was used as the dimensionless shear stress, a value used by past researchers in the Puget

Sound region (Konrad, 2000). Thus, when bankfull shear stress is larger than critical shear stress, the bed substrate dislodges and moves (or becomes mobile), moving to a place downstream. The shear stress ratio (bankfull/critical) describes the mobility of the bed in this way: 1) if the ratio equals one, then forces from the bed and flow are equal, and there is no mobility; 2) if the ratio is greater than one, the bed is mobile, possibly leading to erosion; and 3) if the ratio is less than one, the bed is not mobile, and the bankfull shear stress has not yet reached a critical level. The ratio was used to: 1) make comparisons to the other geomorphic variables of study to determine any trends present, and 2) determine which points of measurement along each reach were considered to be mobile (since different cross-sections can have different shear stress values).

Shear stress values and mobility were determined for the single cross-section, and these values were compared to the mean shear stress values of the streams. Furthermore, as shear stress may be based either on D_{50} or D_{84}, both methods were used to calculate it, and additional comparisons were made.

In addition, the standard error of the mean was determined for each variable (based on one standard deviation from the mean). The standard error was used to calculate the 95% confidence limits for each variable mean. The limits are represented on the comparison plots as error bars for each variable and reach.

Comparison of the Coefficients of Variation of the Variable Means and the Imperviousness of each of the Study Watersheds

This portion of the study was to test the hypothesis that complexity decreases with increasing imperviousness (urbanization). The Coefficient of Variation compares the relative amounts of variation of a certain variable among populations having different means; it is independent of the unit of measurement and is expressed as a percentage (Sohkal and Rolf, 1987). The CV also ignores sample size, which is appropriate for this study. Generally, the higher the Coefficient of Variation for a population, the more variable is that population. Therefore, a high CV can represent a more complex stream site. These coefficients were determined to describe the variability of the variables, and therefore used to compare the complexity of the streams sites to each other. The coefficients were plotted against percent imperviousness to investigate relationships (if present) to stream complexity.

In addition, hypothesis testing was carried to test if the slope coefficient was equal to zero (null hypothesis). Regressions were done for all comparisons between percent imperviousness and the coefficients of variation of the variables being studied. Results of these tests were then collated for analysis.

Results

The results section is organized as follows: 1) watershed characterization; 2) relationship of land cover to percent imperviousness and land use characterization of each study watershed description of morphology variables and analysis of within-stream variation of all sites; 4) comparison of morphology variables of the reach (means) and single cross-section measurements; 5) comparison of shear stress of the reach (means) and single cross-section measurements; and 6) analysis of complexity of the sites in relationship to urbanization.

Basic Watershed Characteristics

The contributing drainage area for each stream site was calculated (Table 2). All of the watersheds had contributing drainage from lakes, which increased their basin area larger than originally thought. In addition, sites had varying amounts of wetlands, from extensive headwater wetlands to a few pockets of them throughout the watersheds. Both these features may help to attenuate the increased discharge from development in the watershed if the features are located upstream of the sites. Although the larger drainage areas increased the amount of contributing urban land cover in their watershed, the urbanization amounts, shown by percentages, still give a clear picture of the amount of development in each site's watershed. The imperviousness values of the six sites from least to most (urbanized) ranged from 16.4 to 56.5% (Table 6). As can be seen, the imperviousness values tended to cluster into two groups: 1) approximately 16-25% and 2) approximately 43-56%. The initial intention of this study was to investigate sites across a broad range of urbanization. Based on these results, it may not be possible to have a clear picture of stream complexity with the range of imperviousness from 25-40%.

Longitudinal profiles were created for all six streams. The profile was carried out along the length of the study reach in the thalweg; the length depended on the average width of each channel as the methods have described. The figures show the elevation of the thalweg from the upstream to downstream end of each reach. The variation was generally caused by undulations of the bed, sometimes caused by large woody debris (LWD). Undulations of the bed usually, but not always, represented a riffle within the channel. Furthermore, a 'best fit line' was drawn for each profile, and the slope of the regression line represented the gradient of the reach (Figures 1-2). Overall, the elevation decreased from upstream to downstream to downstream for Covington, Cottage Lake, and Miller Creeks, although less of a trend with the latter. Gradient change can be seen within the reach, with the least variation been seen in May Creek.

In general, the morphology of the stream sites was similar. The channel gradient ranged from .01% to .94% (Table 2). Past work in the Puget Sound Lowland region has shown that streams within this gradient range are similar and are called riffle-pool systems (Montgomery and Buffington, 1998). By visual inspection, all stream sites of the study were determined to have riffle-pool systems, with some having fewer pools than others, likely depending on their upstream level of urbanization as well as availability of riparian cover. Pools, however, were not measured or part of this study.

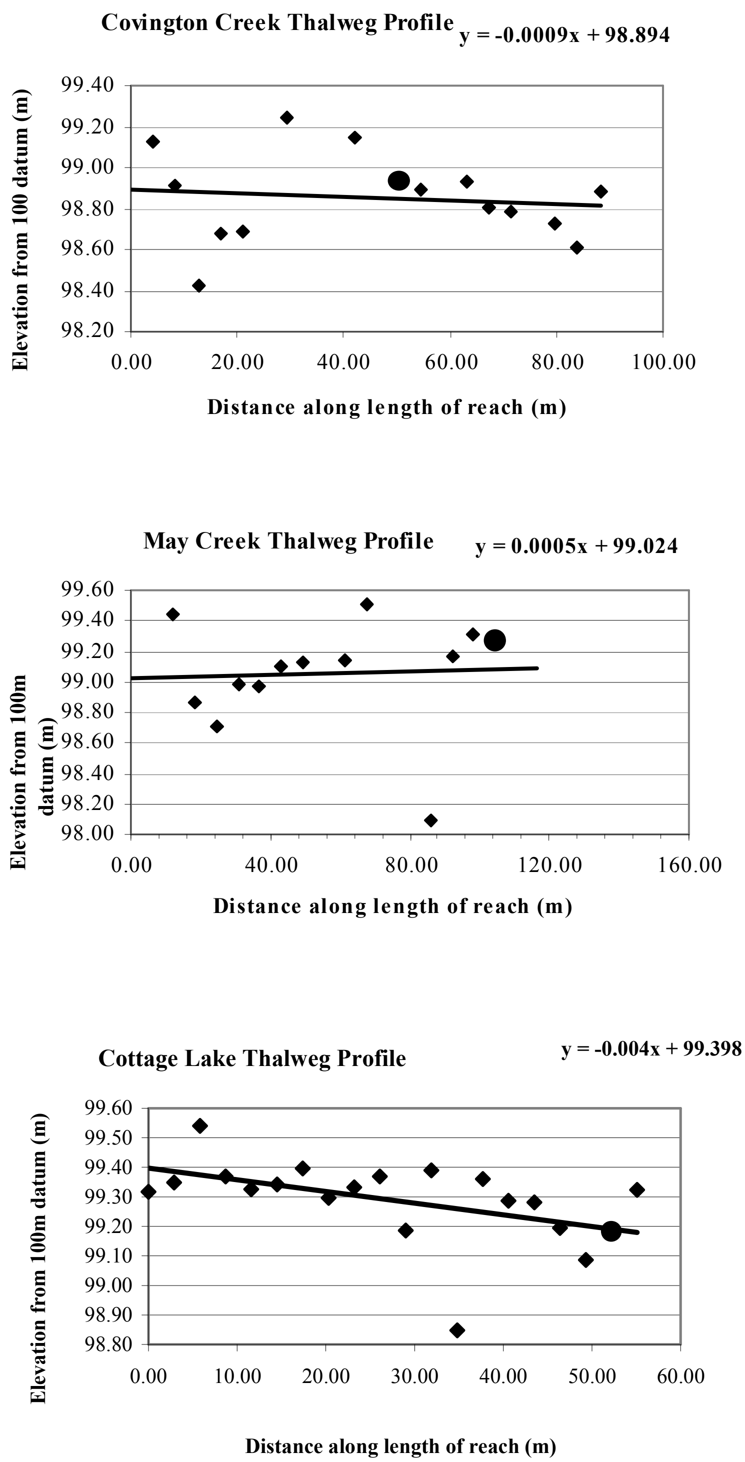
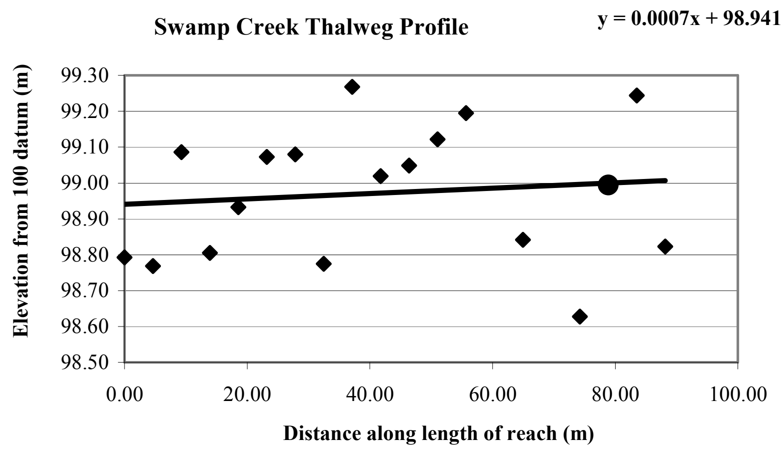
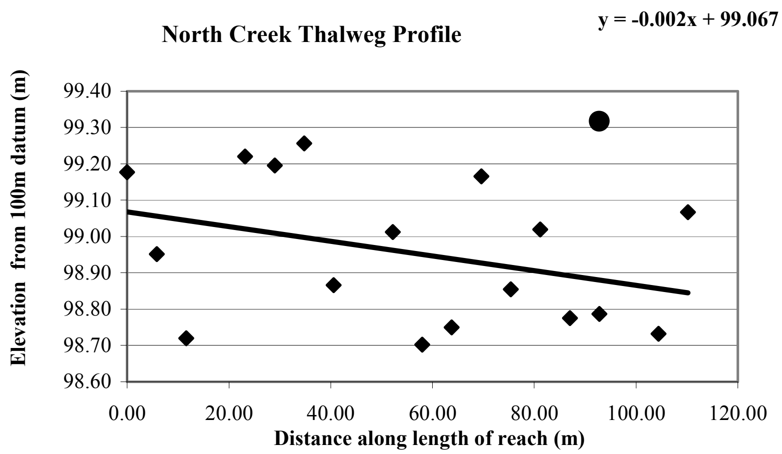


Figure 1. Longitudinal profiles of each stream showing derived slope. Circular symbol represents single cross-section used for reach comparisons (see later section).





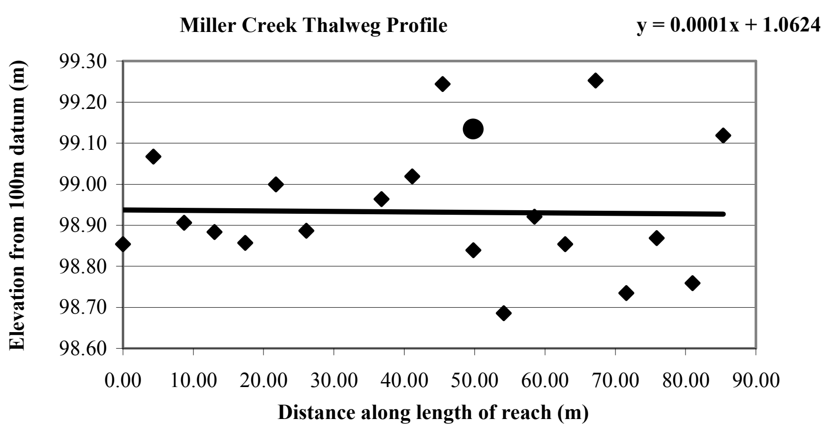


Figure 2. Longitudinal profiles of each stream showing derived slope. Circular symbol represents single cross-section used for reach comparisons (see later section).

Watershed Land Cover and Imperviousness

The results of the spatial analysis and urban land cover calculations allow comparison among study watersheds. The watershed land cover of the six sites range from highly urbanized to highly forested (Table 6 and Figure 3). The types of urban land cover affected the amount of imperviousness in each watershed so that sites with a certain amount of urban land cover did not necessarily mean that the watershed would have the same amount of imperviousness.

				% Total Urban Land Cover				% Total Non-Urban Land Cover		
Stream Sites	**Drainage Area (km2)**	**% Imperviousness**	**% Total Urban Land Cover**	**% Paved Urban**	**% Forested Urban**	**% Grass/ Shrub Urban**	**% Bare Earth**	**% Forested**	**% Grass/ Shrubs/ Crops**	**% Water**
Covington Creek	48.403	16.36	29.31	2.43	18.31	8.56	0.84	61.72	5.91	2.216
May Creek	45.065	22.27	37.72	2.39	18.88	16.45	0.73	54.35	6.92	0.276
Cottage Lake Creek	30.729	25.48	52.99	1.90	40.44	10.66	0.49	38.97	6.34	1.210
Swamp Creek	50.827	43.28	67.10	12.57	27.77	26.77	1.39	22.51	8.45	0.545
North Creek	31.957	46.45	72.73	12.31	28.89	31.53	0.83	17.37	7.79	1.279
Miller Creek	20.608	56.48	81.08	16.00	21.22	43.86	1.27	9.96	7.02	0.677

Table 6. Urban land cover and imperviousness for study sites.

For example, it was determined that Cottage Lake Creek has approximately 53% urban land cover. However, the greatest amount of land cover within that calculation was considered forested urban. As forested urban was determined by Hill et al. (2000) to have the least amount of imperviousness, the imperviousness for Cottage Lake turned out to be 25.5%, less than half of its urban land cover percentage. On the other hand, Miller Creek, with 81.1% urban land cover, had 16% paved urban cover and only 21% forested urban cover. Thus, its imperviousness value of 56.5% was not as different from its urban land cover as was Cottage Lake (Figure 4). For this land cover type classification, *forested urban* was found to misclassified pixels, where results were both more and less urban than expected (Hill et al., 2000). This result does confirm Hill et al.'s findings. Despite this, total urban land cover and imperviousness were found to be highly correlated ($R^2 = .9552$), and thus, it was determined that this classification was more than adequate for this study (Figure 5). In addition, hypothesis testing (null hypothesis: mean = 0) showed that the p value was less than .05 (95% confidence), so the null hypothesis was rejected (Table 7). This means that change in urban land cover can change percent imperviousness, further supporting that imperviousness is a solid measure for urban land cover.

Furthermore, an additional measurement that may act well with percent imperviousness to determine changes according to urbanization is percent forested. The comparison of percent forested to both percent imperviousness and percent urban land cover show a negative relationship between the prior and each of the two latter types. As can be seen, percent forested incrementally decreases with increases in either percent urban land cover or imperviousness (Figure 6). This relationship is strengthened by a hypothesis test (null hypothesis: mean = 0) that showed the p value was less than .05 (95% confidence), so the null hypothesis was rejected (Table 8). This means that percent forested does decrease (negative slope) when compared to both urban land cover and percent imperviousness.

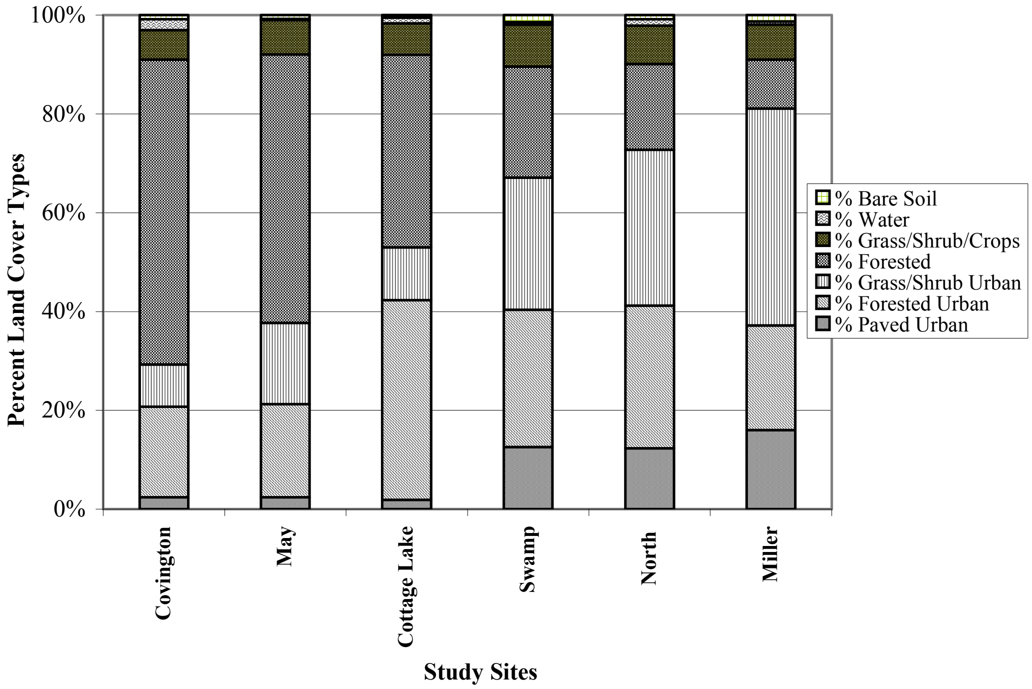


Figure 3. Land cover types of drainage areas of each of six stream sites shown by percentages.

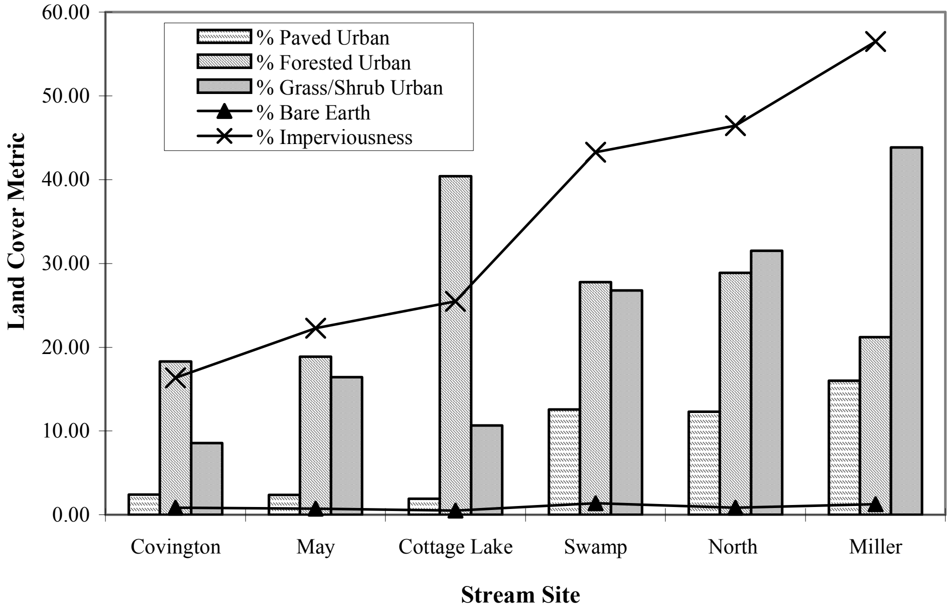


Figure 4. Comparison of urban land cover to imperviousness by stream site. Bare earth was considered part of total urban land cover based on its imperviousness value.

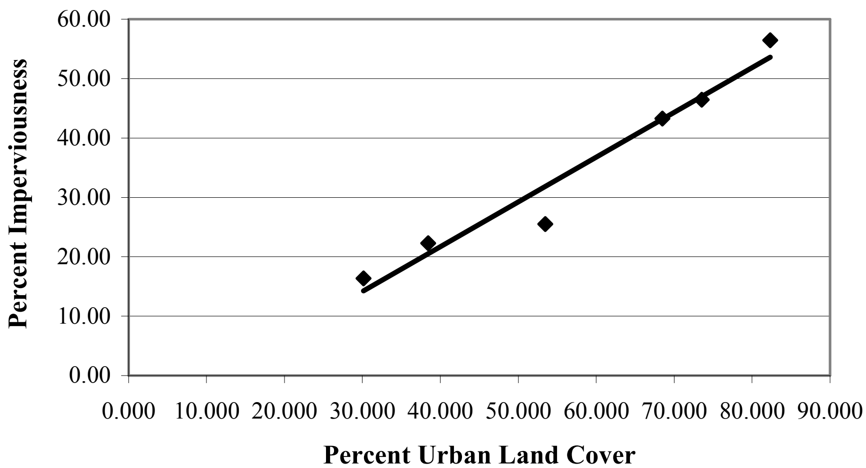


Figure 5. Comparison of urban land cover to imperviousness (by percentage). Null hypothesis was rejected, supporting this comparison ($p < .05$).

Urban Land Cover and Imperviousness: Slope Coefficient Test; Null Hypothesis: Slope = 0					
Slope Coeff. Value	**R^2**	**p-Value**	**Lower 95%**	**Upper 95%**	**Reject Null Hypothesis**
0.75344461	0.955153507	0.000766	0.526803	0.980086	YES

Table 7. Slope coeffiecient test for comparison of urban land cover and imperviousness; 95% confidence (Figure 5).

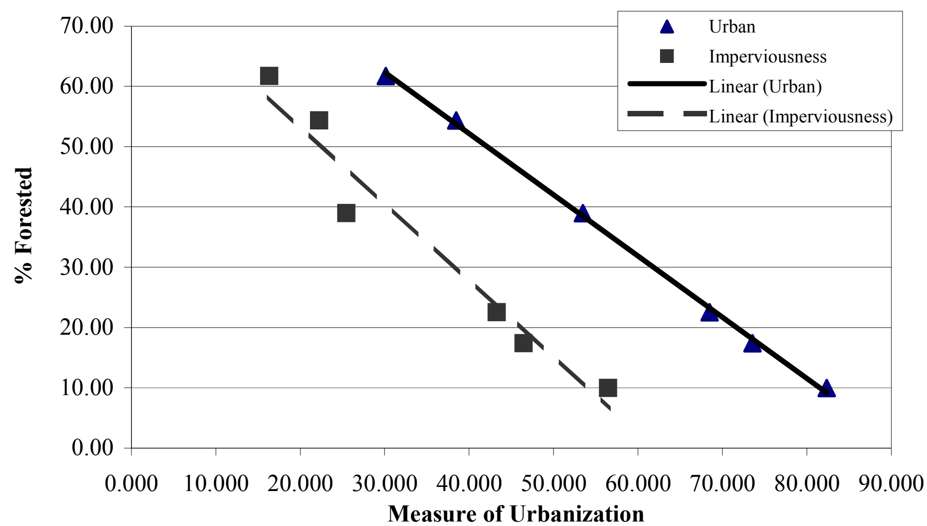


Figure 6. Comparison of urbanization to forested land cover (by percentage). Null hypothesis was rejected, supporting this comparison ($p < .05$).

Measures of Urbanization and Forested Area: Slope Coefficient Test; Null Hypothesis: Slope = 0						
Comparison	**Slope Coeff. Value**	**R^2**	**p-Value**	**Lower 95%**	**Upper 95%**	**Reject Null Hypothesis**
Urban land cover/forested	-1.016028947	0.998869	4.8E-07	-1.06349308	-0.968564813	YES
Imperviousness / forested	-1.288366409	0.954563	0.000786	-1.678579592	-0.898153225	YES

Table 8. Slope coeffiecient test for comparison of measures of urbanization and imperviousness; 95% confidence (Figure 6).

In-Stream Complexity

A minimum of seventeen cross sections (with the initial goal of twenty) were carried out in each of the six study reaches. This was done in order to capture the complexity, or heterogeneity, of the reaches, which typical standardized methods do not do (Rosgen, 1996; Harrelson, 1994). For example, to observe the change (variability) of channel width in the Covington Creek reach, the width at each cross-section along the reach length was plotted against the distance at which each cross-section was done. Usually, a site to carry out one cross-section is chosen in order to determine the characteristics of the entire stream (Rosgen, 1996; Harrelson, 1994). As can be seen, the complexity of each morphological variable by stream reach is varied and changes at least every .5m of the reach. The numerous cross-sections carried out in the field allow the illustration of the complexity that exists within a channel, even within the most impervious reach, Miller Creek. The complexity is represented as standard deviations of each variable (Table 9). In-stream variation for all morphological variables measured in the field and later calculated are shown (Table 9).

										Bed Substrate			Relative Roughness		Heterogeneity	Sorting
Streams	**Statistics**	**Imperviousness (%)**	**Gradient (%)**	**BW (m)**	**BD (m)**	**w/d ratio**	**Cross-Sec Area (m^2)**	**Wetted Perimeter (m)**	**Hydraulic Radius (m)**	**D16 (mm)**	**D50 (mm)**	**D84 (mm)**	**d/D50**	**d/D84**	**D84/D50**	**(D84-D16)/2**
Covington	**Average**	16.36	0.09	5.450	0.914	6.470	4.969	3.849	1.320	14	68	144	18.080	6.917	2.425	64.944
	SD			1.203	0.245	2.760	1.662	1.391	0.292	9.009	30.629	30.469	14.361	3.007	0.827	12.816
May	**Average**	22.27	0.94	8.801	0.724	14.120	6.258	4.921	1.446	9	34	82	24.134	9.522	2.734	36.050
	SD			4.083	0.336	8.238	3.386	1.295	0.899	8.780	16.141	22.475	15.655	6.508	1.020	8.501
Cottage Lake	**Average**	25.48	0.40	4.397	0.631	7.489	2.688	3.927	0.704	7	30	83	24.100	7.934	2.975	38.225
	SD			1.129	0.135	3.194	0.565	0.824	0.199	4.904	10.455	22.486	11.591	2.126	0.907	11.460
Swamp	**Average**	43.28	0.08	5.732	0.939	6.399	5.288	4.394	1.237	9	36	89	41.277	13.752	2.824	39.763
	SD			2.587	0.169	3.039	2.545	1.218	0.462	6.643	21.575	39.316	37.735	8.838	0.911	17.701
North	**Average**	46.45	0.20	5.704	0.886	6.719	5.036	4.521	1.183	8	26	66	40.821	14.903	2.730	29.100
	SD			1.440	0.181	2.250	1.558	1.214	0.430	3.992	10.483	21.404	21.475	5.657	0.900	10.039
Miller	**Average**	56.48	0.01	5.782	0.906	6.632	5.183	3.582	1.838	7	26	57	46.239	17.829	2.477	25.000
	SD			1.660	0.152	2.552	1.507	1.764	1.124	5.787	11.966	19.057	32.112	7.490	0.827	8.243

Table 9. In-Stream Variation (Variable averages and their standard deviations by stream site); SD = standard deviation.

The variables with the highest standard deviations, and thus the most variation when compared to the mean, are the substrate and variables related to substrate, such as sorting and relative roughness. The least variation observed by the standard deviations involve channel dimensions – hydraulic radius and depth. Furthermore, substrate size decreases from the least urbanized to the next least urbanized at D_{16}, D_{50}, and D_{84}. However, although the trend may continue to the next least urbanized, it does appear to be a trend for all the sites.

Another measure of in-stream complexity can be seen by the substrate distributions for each reach. These distributions show how stream bed substrate changes along the length of the reach. According to past work, channels lose their complexity with increasing urbanization. This would hold true for bed substrate as well. In addition, some researchers agree that sediment supply decreases with increasing urbanization. This leads to finer bed substrate, with coarser substrate moved downstream, and overall decrease in bed heterogeneity. However, substrate distributions for these study sites show do not support this. Swamp and Miller Creeks, both highly imperviousness, show a large range of substrate, with both fines and cobbles within the reach (Figure 7).

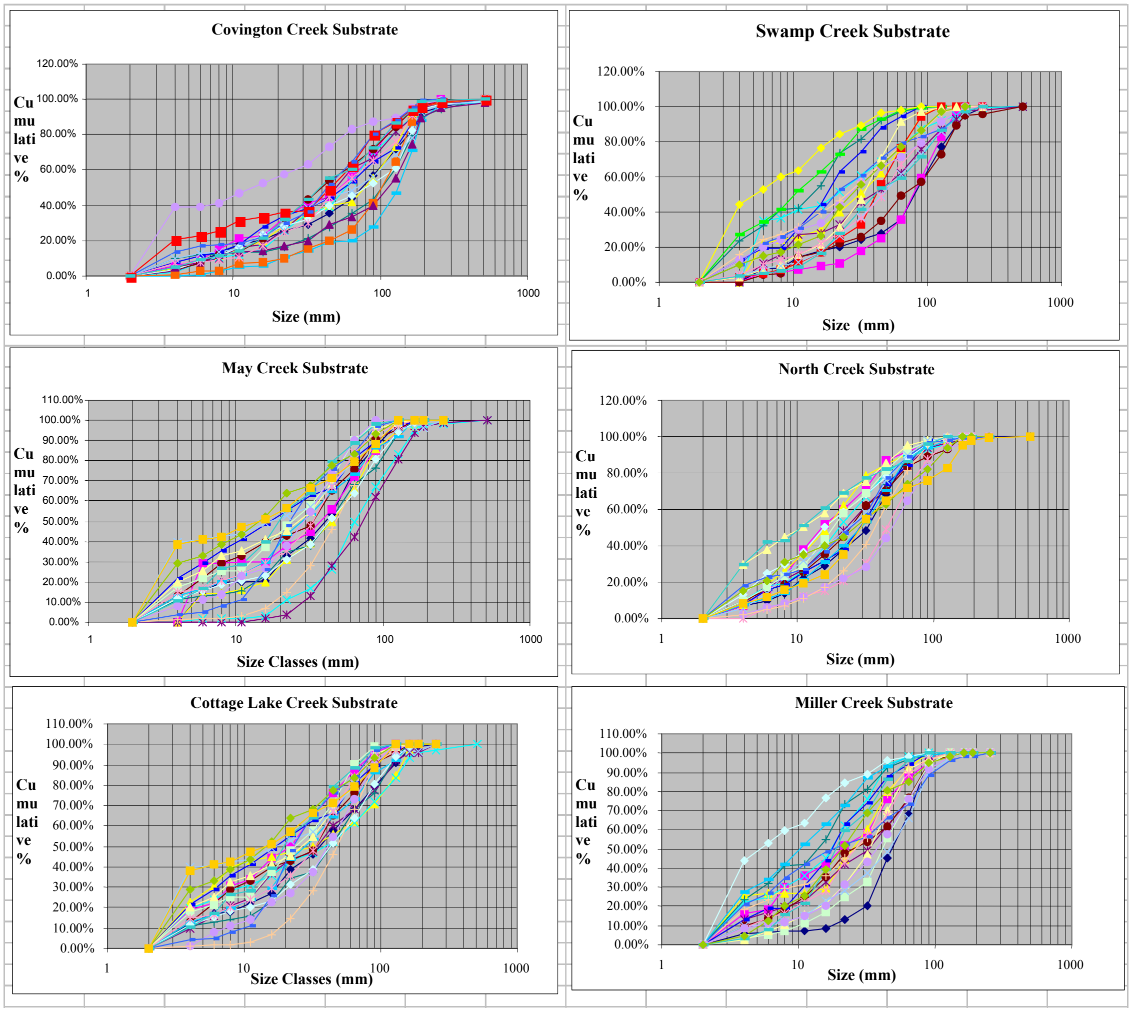


Figure 7. Reach substrate distributions of each site.

<u>*Comparison of Averaged Morphological Variables to Values of a Single Cross-Section of Each Reach*</u>

For this analysis, single cross-sections were chosen immediately after the most downstream riffle of each reach; thus, six cross-sections were chosen in total for all of the six sites. The morphological variables of the single cross-section of each reach were compared to the variable means (by reach). This was done to investigate how well the single measurements describe the reach complexity as compared to the mean values.

The following variables were compared between the above-mentioned parameters: 1) width; 2) depth (and width/depth ratio); 3) cross-section area; 4) wetted perimeter; 5) hydraulic radius; 6) substrate size (D_{16}, D_{50}, D_{84}); 7) relative roughness (based on D_{50} and D_{84}); 8) substrate heterogeneity (D_{84}/D_{50}); and 9) substrate sorting ((D_{84}-D_{16})/2) (Tables 9 and 10).

Single Cross-Section Variables														
								Bed Substrate (mm)			**Relative Roughness**	**Relative Roughness**	**Heterogeneity**	**Sorting**
Stream Sites	**% Imperviousness**	**BW (m)**	**BD (m)**	**w/d ratio**	**Cross-Sec Area (m^2)**	**Wetted Perimeter (m)**	**Hydraulic Radius (m)**	**D16**	**D50**	**D84**	**d/D50**	**d/D84**	**D84/D50**	**(D84-D16)/2**
Covington Creek	16.36	5.935	0.960	6.183	5.697	4.299	1.325	37	133	184	7.217	5.217	1.383	73.500
May Creek	22.27	4.920	0.541	9.100	2.660	3.080	0.864	6	21	55	25.745	9.830	2.619	24.500
Cottage Lake Creek	25.48	3.282	0.690	4.758	2.264	3.877	0.584	4	22	59	31.356	11.692	2.682	27.500
Swamp Creek	43.28	4.085	1.135	3.600	4.635	3.489	1.328	5	31	75	36.601	15.129	2.419	35.000
North Creek	46.45	4.942	0.964	5.128	4.763	4.532	1.051	4	25	56	38.551	17.210	2.240	26.000
Miller Creek	56.48	5.535	1.189	4.656	6.580	4.334	1.518	5	18	41	66.044	28.995	2.278	18.000

Table 10. Measured and calculated variables of single cross-section.

These plots were studied to determine if the single cross-section adequately described the reach morphology of the sites. The error bars for each of the mean variables (calculated from the standard error of the mean) can be used to assess whether the single cross-section measurements are equal to the true population mean (estimated by the sample mean) (Table 11). An equality line (1:1 line) was drawn for each plot. At any point on the line where the single cross-section measurement and the mean meet (are equal), it can be concluded that the single measurement is equal to the mean. If the error bars do not touch the line, it can be concluded that the single cross-section measurement is significantly different from the mean variable. The error bars increase that margin for the single cross-sections, such that if the error bar crosses the equality line (even though the mean value does not), it can also be concluded that the single cross-section measurement is within the range of the mean. For the most part, the single cross-section values did not equal the same values as the mean reaches (Figures 8-20). Those variables that showed more equality to the reach means are relative roughness (based on D50), heterogeneity (D84/D50), sorting, hydraulic radius, and wetter perimeter.

Standard Error of Mean (SE) (Based on one Standard Deviation)														
								Bed Substrate (mm)			Rel. Roughness	Rel. Roughness	Heterogeneity	Sorting
Stream Sites	n (# in sample)	BW (m)	BD (m)	w/d ratio	Cross-Sec Area (m^2)	WP	Hyd. Red.	D16	D50	D84	d/D50	d/D84	avg D84/D50	(D84-D16)/2
Covington	19	0.276	0.056	0.633	0.381	0.319	0.067	2.067	7.027	6.990	6.990	0.690	0.190	0.690
May	17	0.990	0.082	1.998	0.821	0.314	0.218	2.130	3.915	5.451	3.797	1.578	0.247	2.062
Cottage Lake	20	0.253	0.030	0.714	0.126	0.184	0.044	1.097	2.338	5.028	2.592	0.475	0.203	2.563
Swamp	19	0.593	0.039	0.697	0.584	0.279	0.106	1.524	4.950	9.020	8.657	2.028	0.209	4.061
North	20	0.322	0.041	0.503	0.348	0.271	0.096	0.893	2.344	4.786	4.802	1.265	0.201	2.245
Miller	19	0.381	0.035	0.585	0.346	0.405	0.258	1.328	2.745	4.372	7.367	1.718	0.190	1.891

Table 11. Standard error of means for morphology variable averages of each stream site.

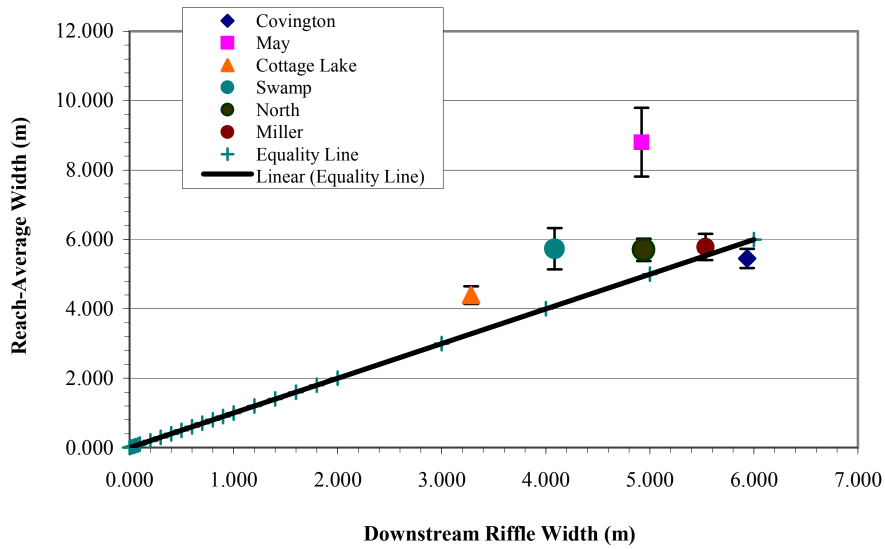


Figure 8. Comparison of averaged-width of each reach and single cross-section widths.

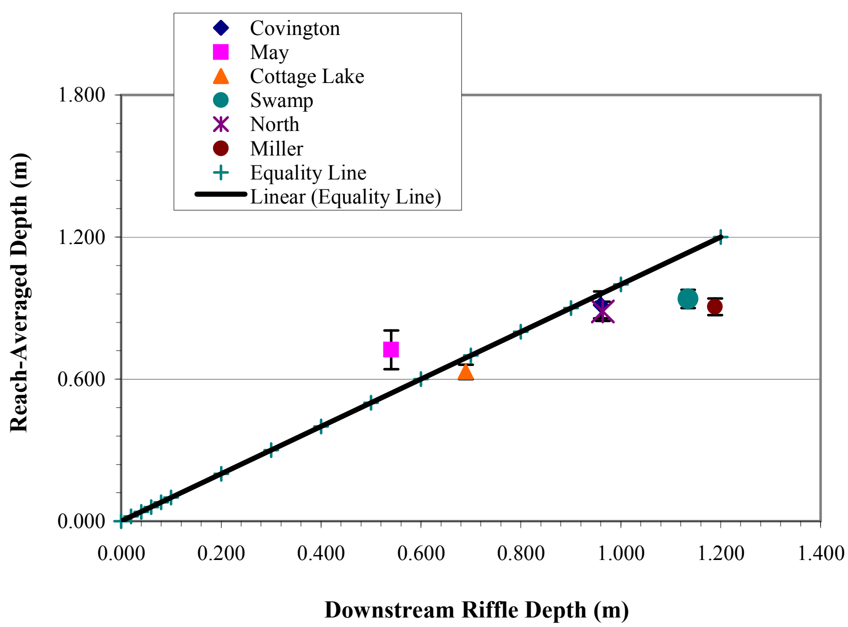


Figure 9. Comparison of averaged-depth of each reach and single cross-section depths.

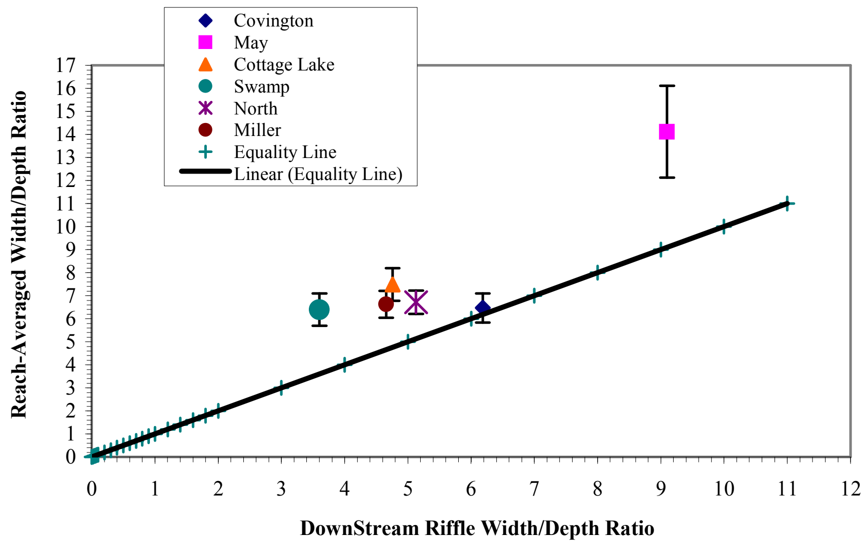


Figure 10. Comparison of averaged-width/depth ratio of each reach and single cross-section width/depth.

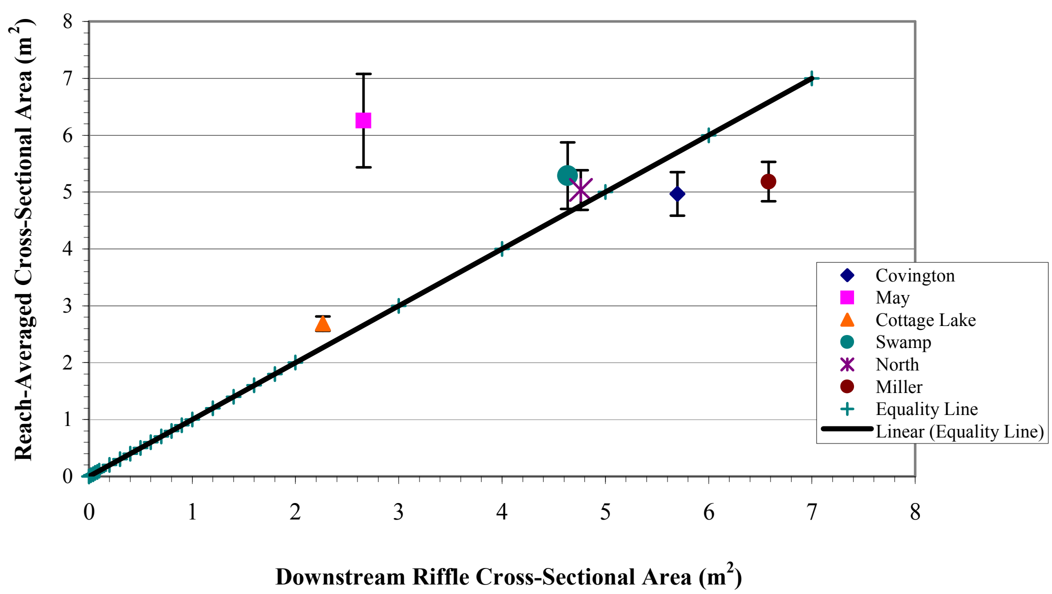


Figure 11. Comparison of average cross-section areas of each reach and single cross-section area.

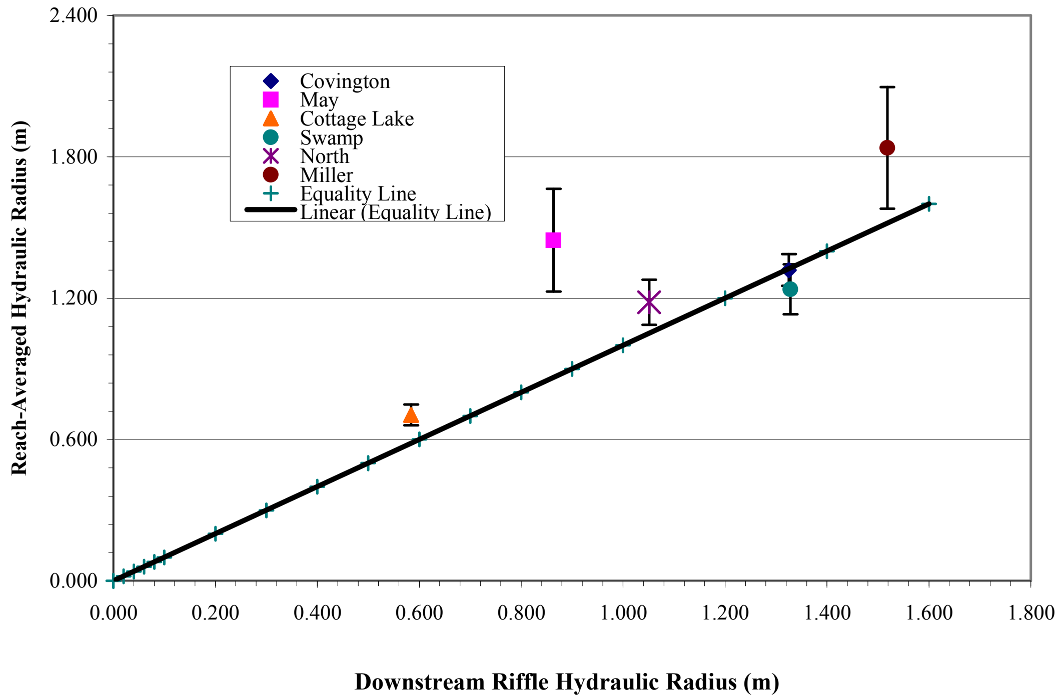


Figure 12. Comparison of averaged-hydraulic radius of each reach and single cross-section hydraulic radius.

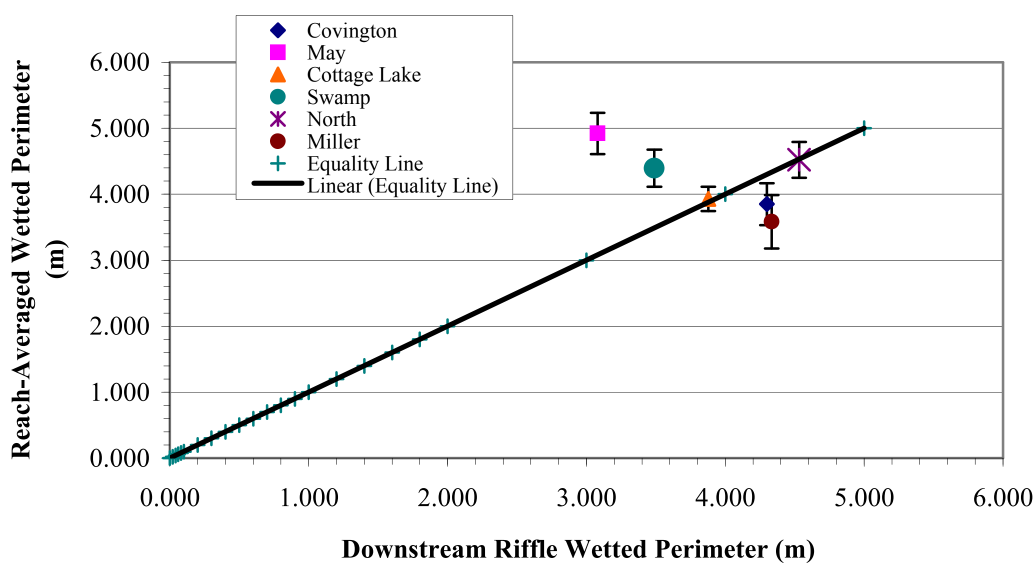


Figure 13. Comparison of averaged-wetted perimeter of each reach and single cross-section wetted perimeter.

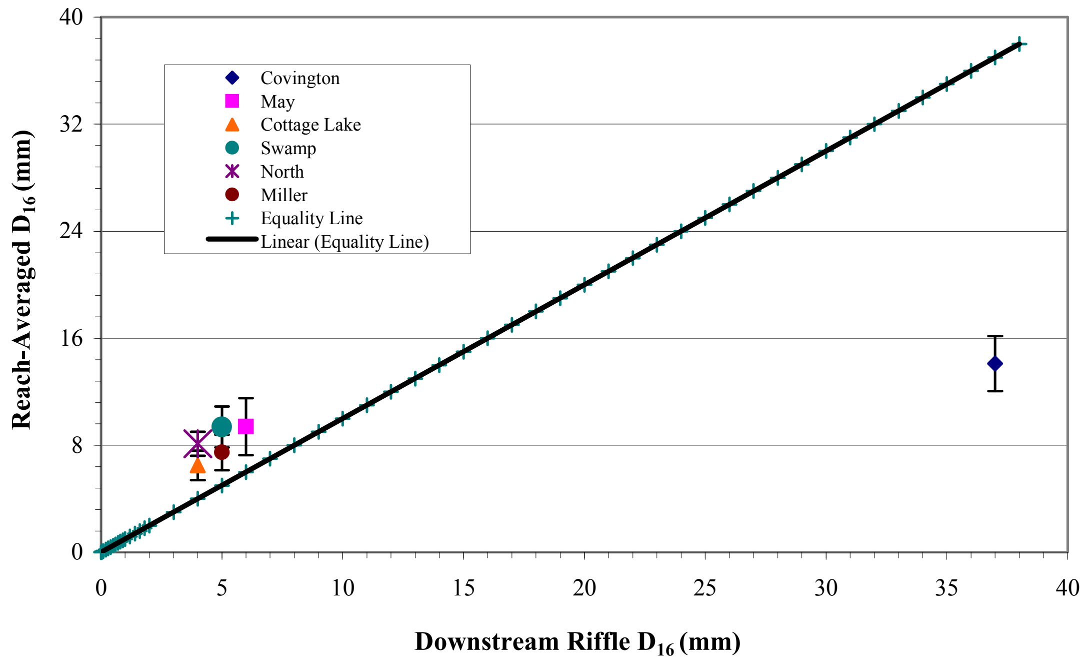


Figure 14. Comparison of averaged-D_{16} of each reach and single cross-section D_{16}.

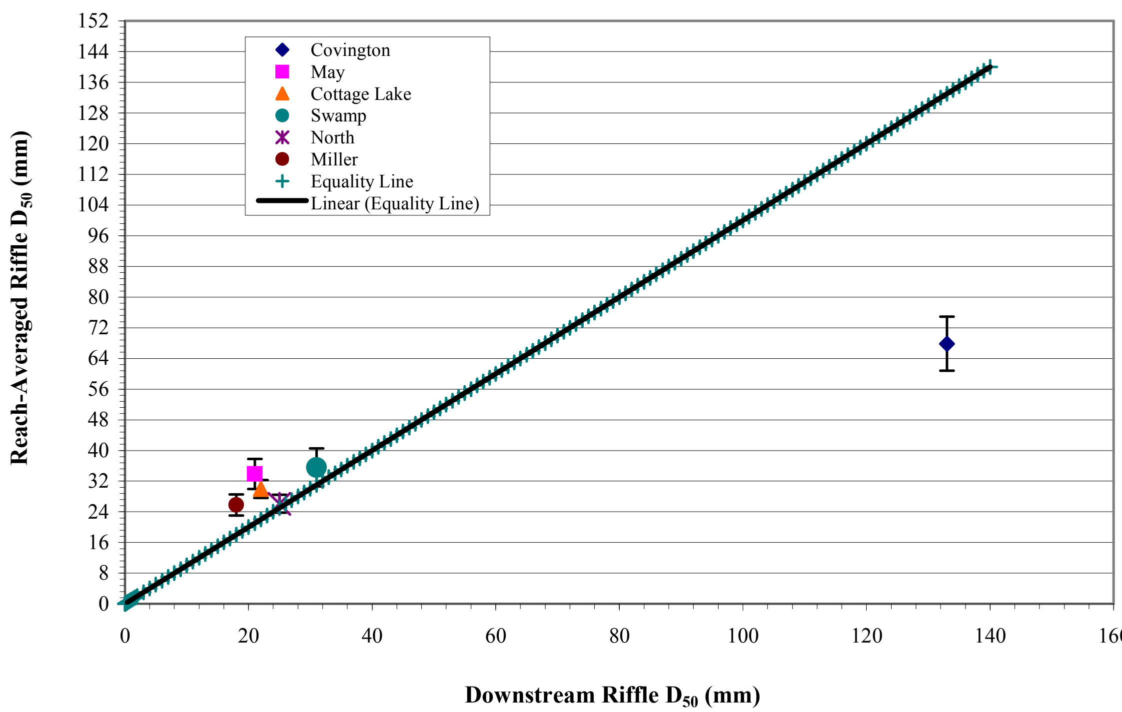


Figure 15. Comparison of averaged-D_{50} of each reach and single cross-section D_{50}.

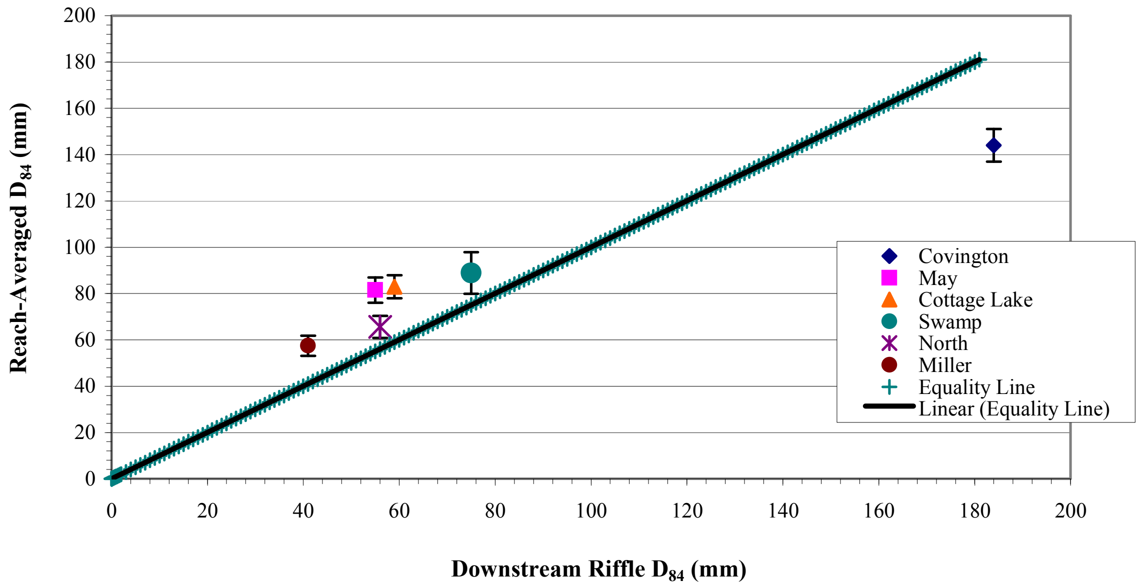


Figure 16. Comparison of averaged-D_{84} of each reach and single cross-section D_{84}.

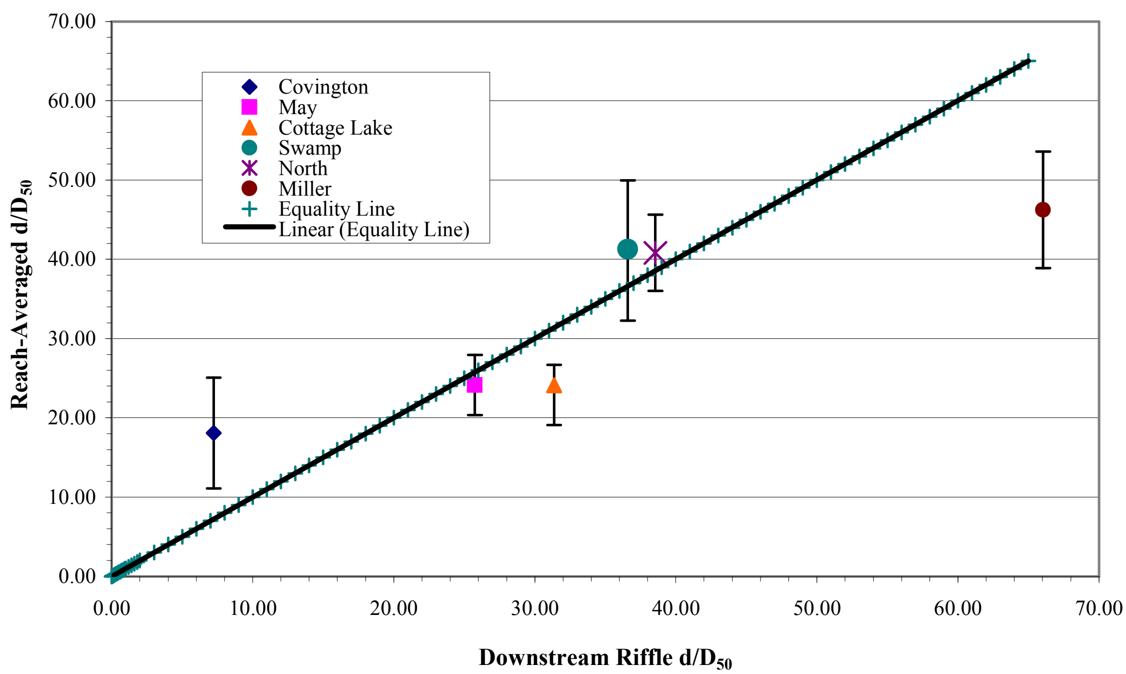


Figure 17. Comparison of averaged-d/D_{50} of each reach and single cross-section d/D_{50}.

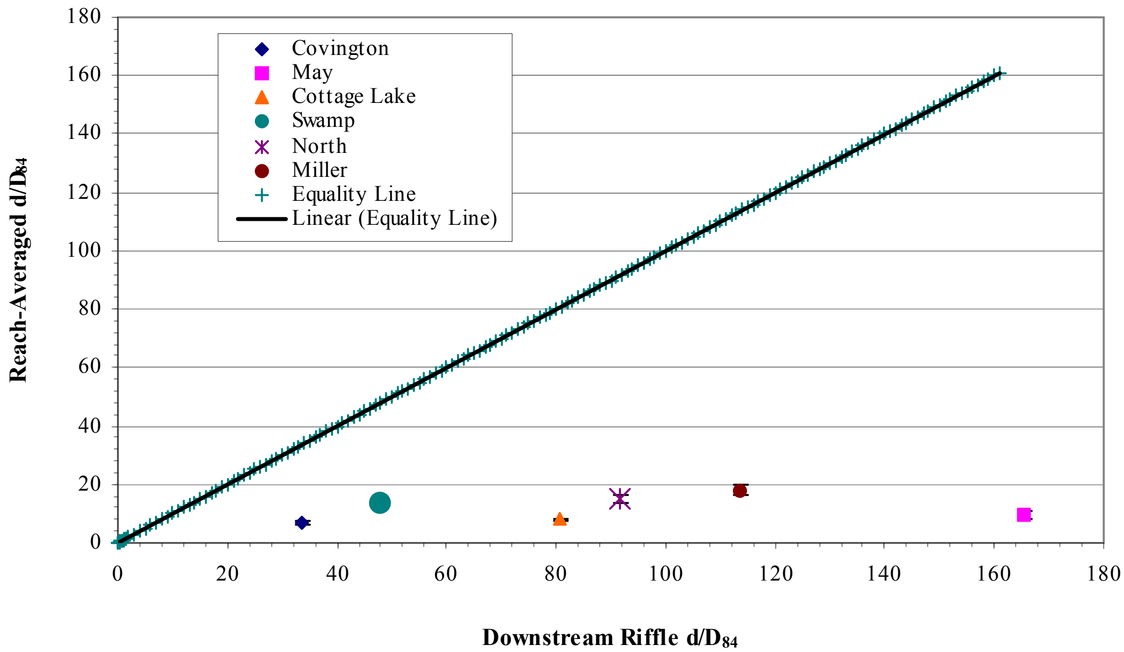


Figure 18. Comparison of averaged-d/D_{84} of each reach and single cross-section d/D_{84}.

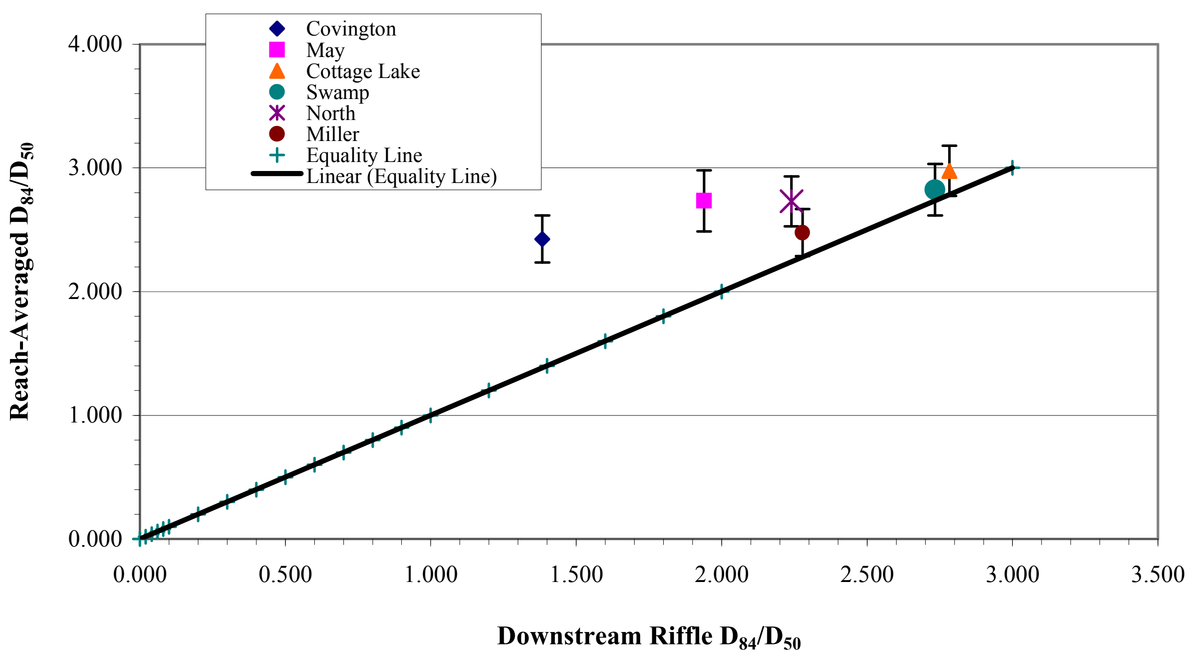


Figure 19. Comparison of averaged-D_{84}/D_{50} of each reach and single cross-section D_{84}/D_{50}.

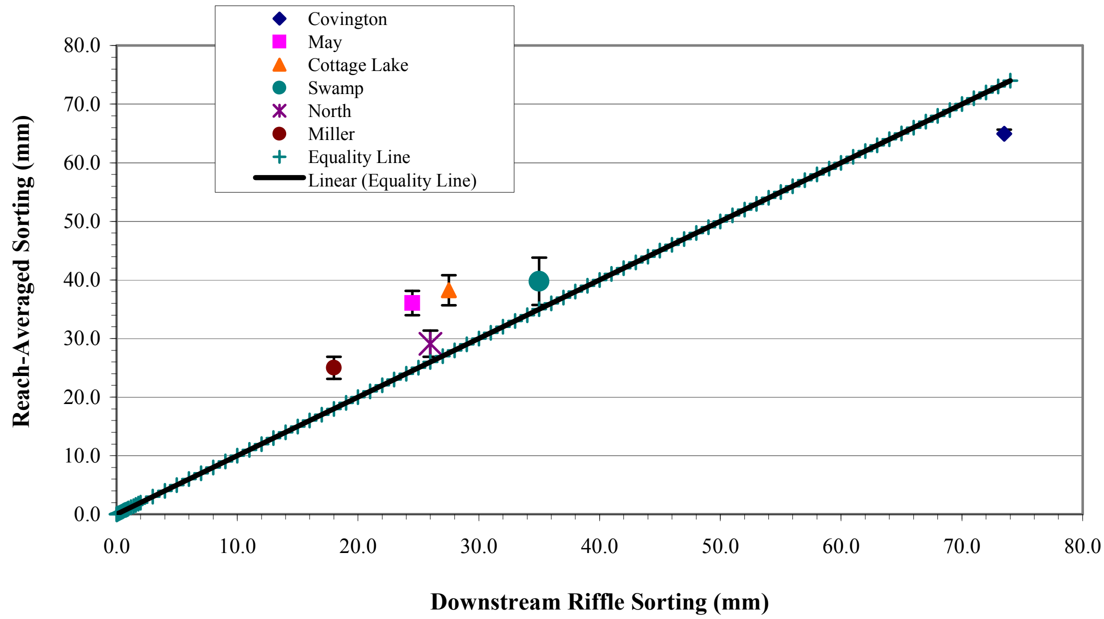


Figure 20. Comparison of averaged-sorting of each reach and single cross-section sorting. Sorting = (D_{84}-D_{16})/2.

Comparison of Averaged and Single Cross-Section Shear Stress of Each Reach

For this analysis, similar comparisons were made as in the prior section. However, instead of morphologic variables, the shear stresses computed from the properties of the single cross-sections were compared to the reach-averaged values. This was done to investigate how well the following variables were compared between the above-mentioned parameters: 1) bankfull shear stress (based on mean depth and hydraulic radius); 2) critical shear stress (based on D_{50} and D_{84}); and 3) shear stress ratio. The calculation of the shear stress ratio (bankfull shear stress/critical shear stress) is explained in the methods.

The shear stress values for the single cross-section can be seen in Table 12, whereas the reach-averaged values for both D_{50} and D_{84} can be seen in Tables 13 and 14.

SINGLE CROSS-SECTION SHEAR STRESS						Bankfull Shear Stress	Critical Shear Stress (D_{50})	Shear Stress Ratios (based on D50)	Critical Shear Stress (D_{84})	Shear Stress Ratios (based on D84)
Stream Sites	**% Imperviousness**	**CS#**	**D_{50} (m)**	**D_{84} (m)**	**Hydraulic Radius (m)**	**τ_{bf} (Hyd.R)**	**τ_{c50}**	**τ_{bf}/t_{c50} (Hyd. Rad.)**	**τ_{c84}**	**τ_{bf}/t_{c84} (Hyd. Rad.)**
Covington Creek	16.40	10	0.133	0.184	1.325	11.687	111	0.105	153.640	0.076
May Creek	22.30	18	0.021	0.055	0.864	4.232	18	0.241	45.925	0.092
Cottage Lake Creek	25.50	2	0.022	0.065	0.584	22.893	18	1.246	54.275	0.422
Swamp Creek	43.30	3	0.031	0.075	1.328	9.113	26	0.352	62.625	0.146
North Creek	46.5	17	0.025	0.056	1.051	20.599	21	0.987	46.760	0.441
Miller Creek	56.5	9	0.018	0.041	1.518	1.488	15	0.099	34.235	0.043

Table 12. Shear stress values for single cross-section of each reach.

Stream	Statistic	% Imperviousness	Avg Hyd Radius (m)	Avg D_{50} (m)	t_{bf} (Hyd.R)	τ_{c50}	τ_{bf}/τ_{c50} (Hyd. Rad)
Covington	**AVG**	16.40	1.320	0.068	11.639	56.641	0.277
	CV		0.292	0.031	2.575	25.575	0.226
May	**AVG**	22.30	1.446	0.034	7.086	28.307	0.265
	CV		0.899	0.016	4.404	13.477	0.221
Cottage Lake	**AVG**	25.50	0.705	0.030	27.616	25.008	1.293
	CV		0.199	0.010	7.814	8.730	0.790
Swamp	**AVG**	43.30	1.237	0.036	8.487	29.708	0.421
	CV		0.462	0.022	3.172	18.015	0.366
North	**AVG**	46.5	1.183	0.026	23.187	21.794	1.216
	CV		0.430	0.010	8.427	8.753	0.594
Miller	**AVG**	56.5	1.838	0.026	1.801	21.534	0.100
	CV		1.124	0.012	1.101	9.991	0.074

Table 13. Averaged-shear stress values for each reach (based on D_{50}). CV=coefficient of variation.

Stream		% Imperviousness	Avg Hyd Radius (m)	Avg D_{84} (m)	t_{bf} (Hyd.R)	τ_{c84}	τ_{bf}/τ_{c84} (Hyd. Rad)
Covington	**AVG**	16.40	0.914	1.320	8.060	11.639	0.073
	CV		0.245	0.292	2.165	2.575	0.032
May	**AVG**	22.30	0.724	1.446	3.548	7.086	0.056
	CV		0.336	0.899	1.648	4.404	0.038
Cottage Lake	**AVG**	25.50	0.631	0.705	24.735	27.616	0.393
	CV		0.135	0.199	5.298	7.814	0.161
Swamp	**AVG**	43.30	0.939	1.237	6.442	8.487	0.113
	CV		0.169	0.462	1.156	3.172	0.073
North	**AVG**	46.5	0.886	1.183	17.373	23.187	0.350
	CV		0.181	0.430	3.556	8.427	0.133
Miller	**AVG**	56.5	0.906	1.838	0.888	1.801	0.021
	CV		0.152	1.124	0.149	1.101	0.009

Table 14. Averaged-shear stress values for each reach (based on D_{84}). CV=coefficient of variation.

As in the reach morphology comparisons, plots were studied to determine if the single cross-section adequately described the reach shear stress of the sites. The error bars for each of the mean variables (calculated from the standard error of the mean) can be used to assess whether the single cross-section measurements are equal to the true population mean (estimated by the sample mean) (Table 15). An equality line (1:1 line) was drawn for each plot. At any point on the line where the single cross-section measurement and the mean meet (are equal), it can be concluded that the single measurement is equal to the mean. If the error bars do not touch the line, it can be concluded that the single cross-section measurement is significantly different from the mean variable. The error bars increase that margin for the single cross-sections, such that if the error bar crosses the equality line (even though the mean value does not), it can also be concluded that the single cross-section measurement is within the range of the mean. The error bars for each of the mean variables (calculated from the standard error of the mean) can be used to assess whether the single cross-section measurements are equal to the true population mean (estimated by the sample mean) (Figures 21-25).

Standard Error of Mean (SE) (Based on one Standard Deviation)						
STREAMS	**n (# in sample)**	**τ_{bf} (Hyd.R)**	**τ_{c50}**	**τ_{bf}/τ_{c50} (Hyd. Rad)**	**τ_{c84}**	**τ_{bf}/τ_{c84} (Hyd. Rad.)**
Covington	19	0.591	5.867	0.052	5.837	0.009
May	17	1.068	3.269	0.054	4.551	0.015
Cottage Lake	20	1.747	1.952	0.177	4.198	0.042
Swamp	19	0.728	4.133	0.084	7.532	0.023
North	20	1.884	1.957	0.133	3.996	0.040
Miller	19	0.253	2.292	0.017	3.651	0.006

Table 15. Standard error of means for shear stress averages of each stream site.

Unlike the morphology comparisons, the single cross-section measurement values are close to the averaged variables. Shear stress ratios (both for D_{50} and D_{84}) showed the most equality to the reach means with as many as five values being equal. In addition, a similar relationship occurs for both bankfull shear stress and critical shear stress (based on D_{50}).

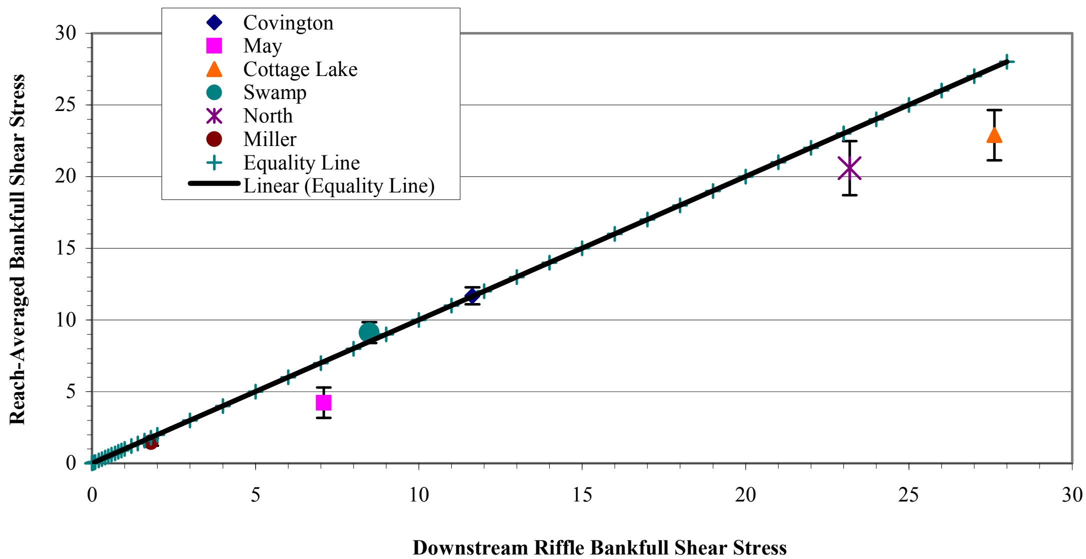


Figure 21. Comparison of averaged-bankfull shear stress of each reach and single cross-section bankfull shear stress.

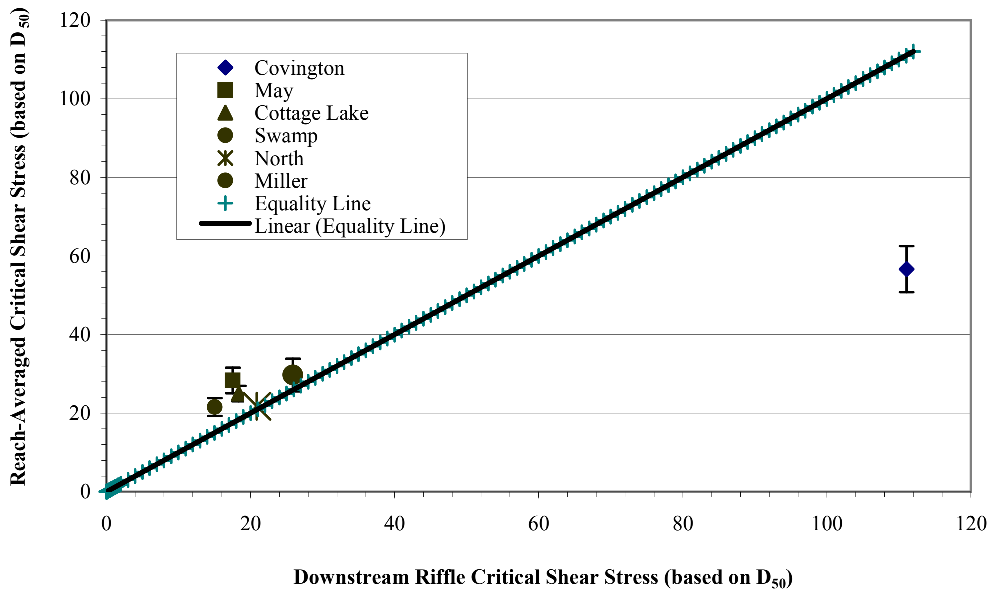


Figure 22. Comparison of averaged-critical shear stress of each reach and single cross-section critical shear stress; values based on D_{50}.

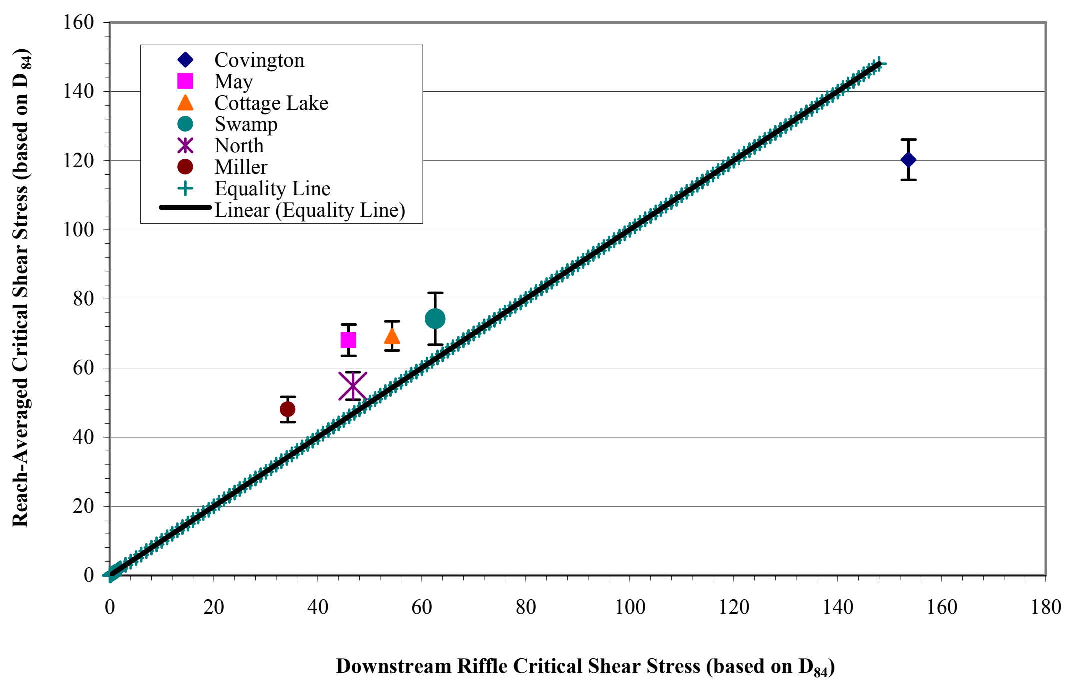


Figure 23. Comparison of averaged-critical shear stress of each reach and single cross-section critical shear stress; values based on D_{84}.

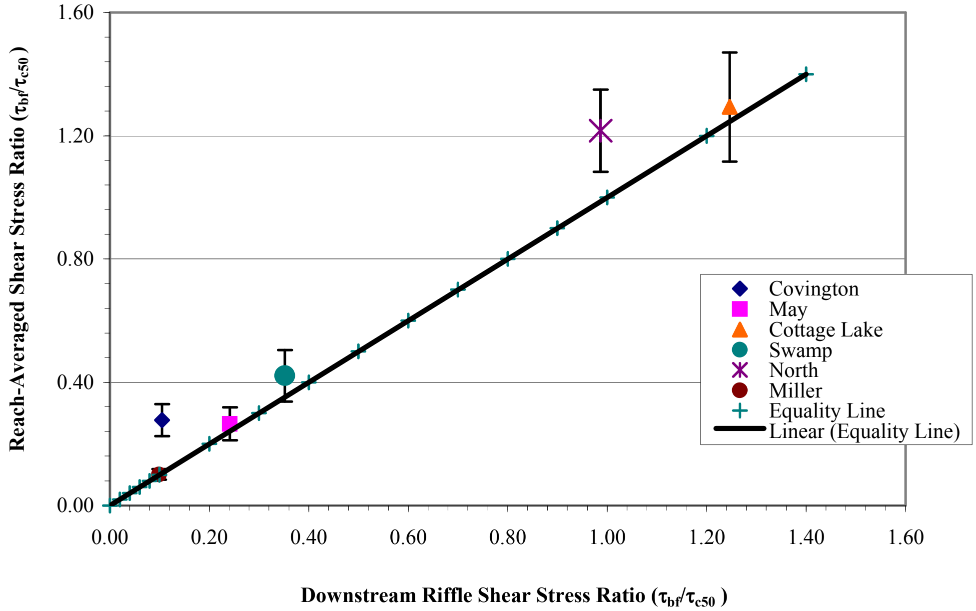


Figure 24. Comparison of averaged-shear stress ratio of each reach and single cross-section shear stress ratio (based on D_{50}).

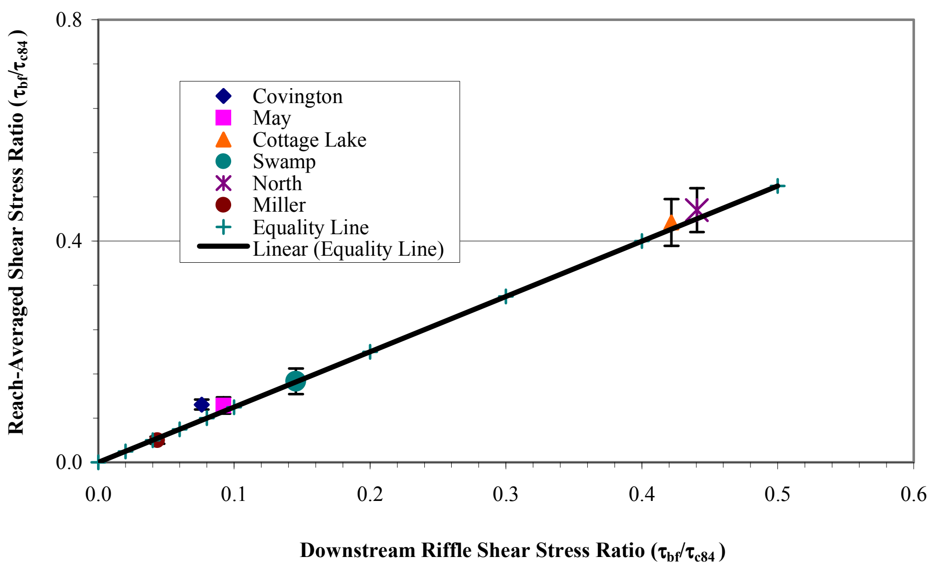


Figure 25. Comparison of averaged-shear stress ratio of each reach and single cross-section shear stress ratio (based on D_{84}).

As explained in data analysis methods, the stream bed is mobile when bankfull shear stress is greater than the critical shear stress within that same reach. The ratio τ_{bf}/τ_{c50} is used to determine the mobility of a cross-section or stream reach. Ratios based on D_{50} and D_{84} were created for both the single cross-section and reach (Table 16).

No cross-sections were found to be mobile using D_{84} as the base substrate size. However, using D_{50}, both Cottage Lake and North Creeks were found to have eleven mobile cross-sections. In addition, Covington, May, and Swamp had one mobile cross-section. Miller had none. Using the downstream's cross-section's shear stress ratio, only Cottage Lake had any mobile cross sections – one. All other sites had no mobility. Mobility signifies that erosion is occurring at that point in the channel.

	SHEAR STRESS RATIOS$_{D50}$ (based on single cross-section)		SHEAR STRESS RATIOS$_{D50}$ (based on reach average)		SHEAR STRESS RATIOS$_{D84}$ (based on single cross-section)		SHEAR STRESS RATIOS$_{D84}$ (based on reach average)	
Stream	τ_{bf}/τ_{c50} (Hyd. Rad.)	# of Mobile CS	τ_{bf}/τ_{c50} (Hyd. Rad.)	# of Mobile CS	τ_{bf}/τ_{c84} (Hyd. Rad.)	# of Mobile CS	τ_{bf}/τ_{c84} (Hyd. Rad.)	# of Mobile CS
Covington	0.105	0	0.277	1	0.076	0	0.105	0
May	0.241	0	0.265	1	0.092	0	0.103	0
Cottage Lake	1.246	1	1.293	11	0.422	0	0.434	0
Swamp	0.352	0	0.421	1	0.146	0	0.147	0
North	0.987	0	1.216	11	0.441	0	0.456	0
Miller	0.099	0	0.100	0	0.043	0	0.040	0

Table 16. Shear stress ratios and mobility for both sites reaches and single cross-sections. CS = cross-section.

Comparison of the Coefficients of Variation of the Variable Means and the Imperviousness of each of the Study Watersheds

Finally, to investigate stream complexity according to differences in percent imperviousness, coefficients of variation for all variables were compared to percent imperviousness of the six sites (six imperviousness values). The values calculated can be found in table below (Table 17).

									Bed Substrate			Relative Roughness		Hetero geneity	Sorting
STREAMS	**Imperviousness (%)**	**Gradient (%)**	**BW CV**	**BD CV**	**W/D CV**	**C/S AREA CV**	**Wetted Perimeter CV**	**Hydraulic Radius CV**	**D_{16} CV**	**D_{50} CV**	**D_{84} CV**	**d/D_{50} CV**	**d/D_{84} CV**	**D_{84}/D_{50} CV**	**$((D_{84}-D_{16})/2)$ CV**
Covington	16.36	0.09	22.083	26.853	42.663	33.449	36.130	22.122	63.844	45.154	21.159	79.431	43.471	34.117	19.734
May	22.27	0.94	46.392	46.452	58.344	54.098	26.314	62.143	93.408	47.612	27.576	64.868	68.351	37.310	23.580
Cottage Lake	25.48	0.40	25.683	21.441	42.653	21.031	20.979	28.308	75.452	34.909	27.108	48.096	26.796	30.491	29.980
Swamp	43.28	0.08	45.129	17.947	47.487	48.125	27.722	37.379	70.912	60.640	44.228	91.420	64.265	32.275	44.515
North	46.45	0.20	25.246	20.471	33.487	30.929	26.856	36.342	49.178	40.163	32.629	52.608	37.957	32.974	34.498
Miller	56.48	0.01	28.704	16.788	38.478	29.075	49.250	61.146	77.427	46.397	33.157	69.449	42.009	33.392	32.971

Table 17. Coefficients of Variation by variable for each stream site. CV=coefficients of variation.

As can be seen from both Table 17 and the Figures 26-35, no trend exists for any of the variables when compared to percent imperviousness. The coefficients of variation do not appear to decrease with increasing imperviousness. The R^2 values for most of the relationships of coefficient of variation to % impervious are very low (e.g. width, w/d).

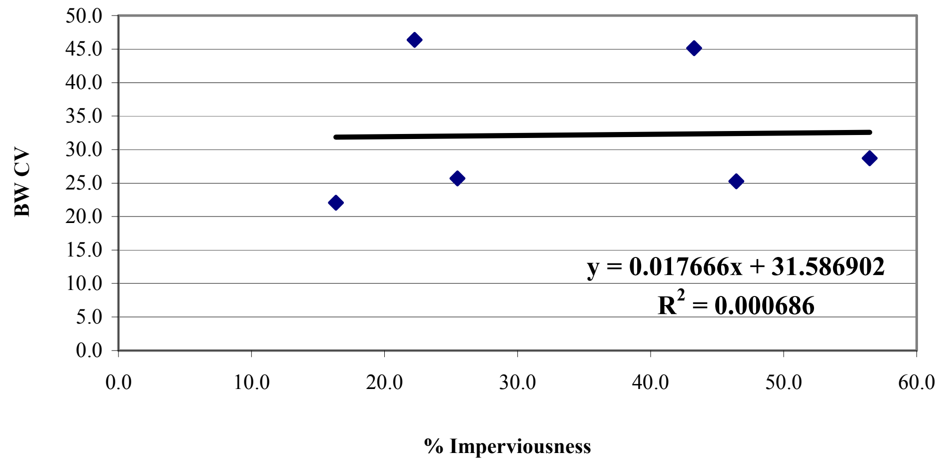


Figure 26. Comparison of bankfull width coefficient of variation of each reach and percent imperviousness; CV=coefficient of variation.

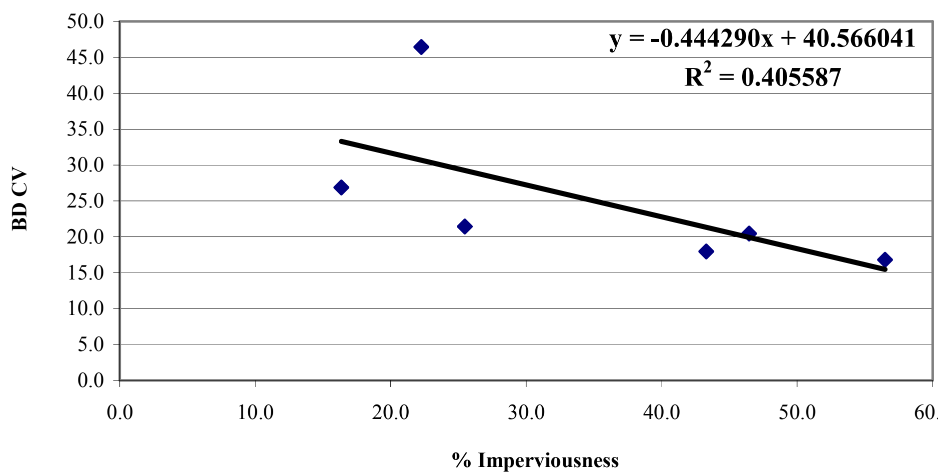


Figure 27. Comparison of bankfull depth coefficient of variation of each reach and percent imperviousness; CV=coefficient of variation.

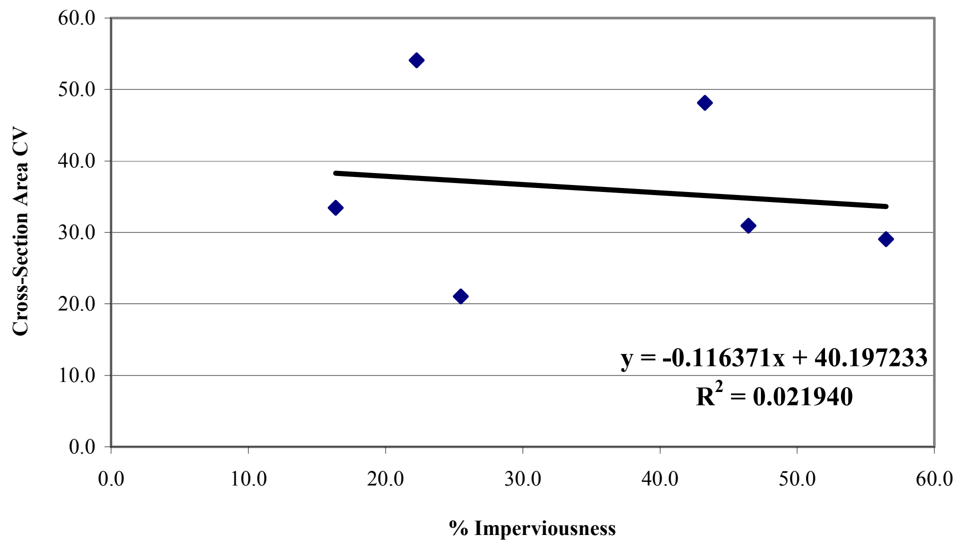


Figure 28. Comparison of cross-section area coefficient of variation of each reach and percent imperviousness; CV=coefficient of variation.

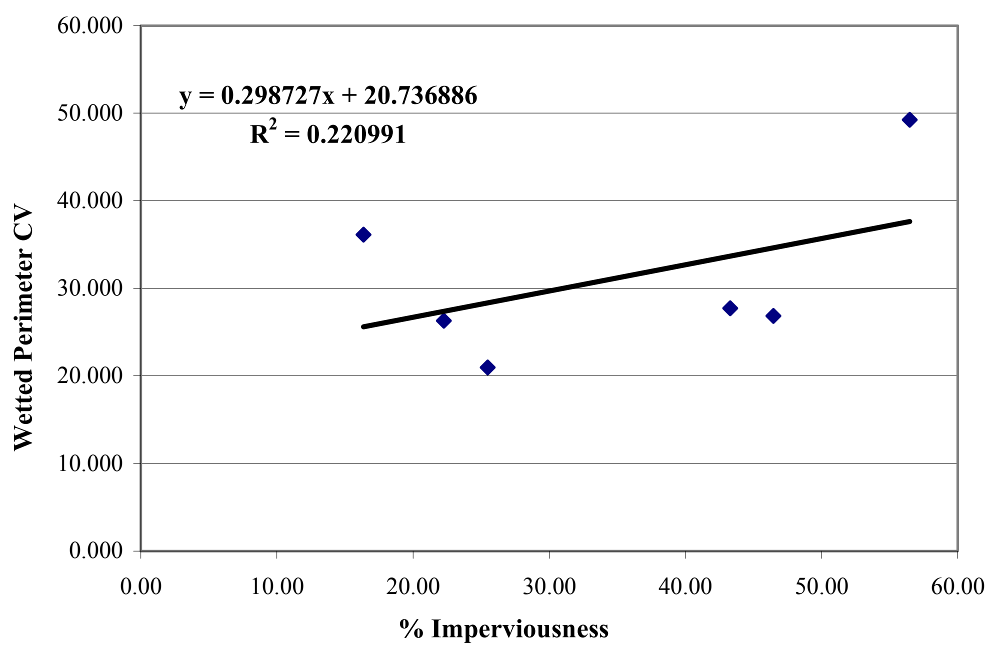


Figure 29. Comparison of wetted perimeter coefficient of variation of each reach and percent imperviousness; CV=coefficient of variation.

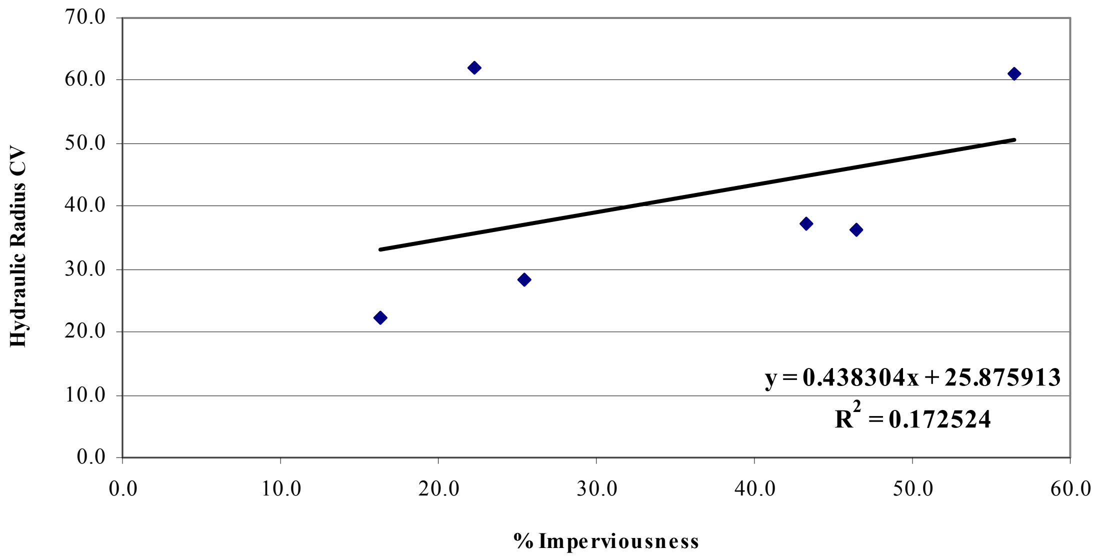


Figure 30. Comparison of hydraulic radius coefficient of variation of each reach and percent imperviousness; CV=coefficient of variation.

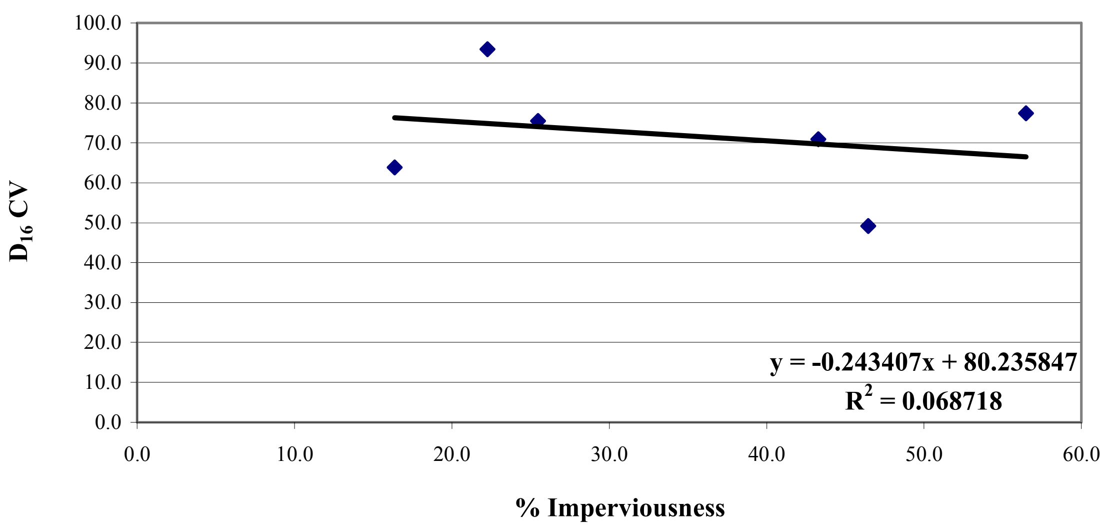


Figure 31. Comparison of D_{16} coefficient of variation of each reach and percent imperviousness; CV=coefficient of variation.

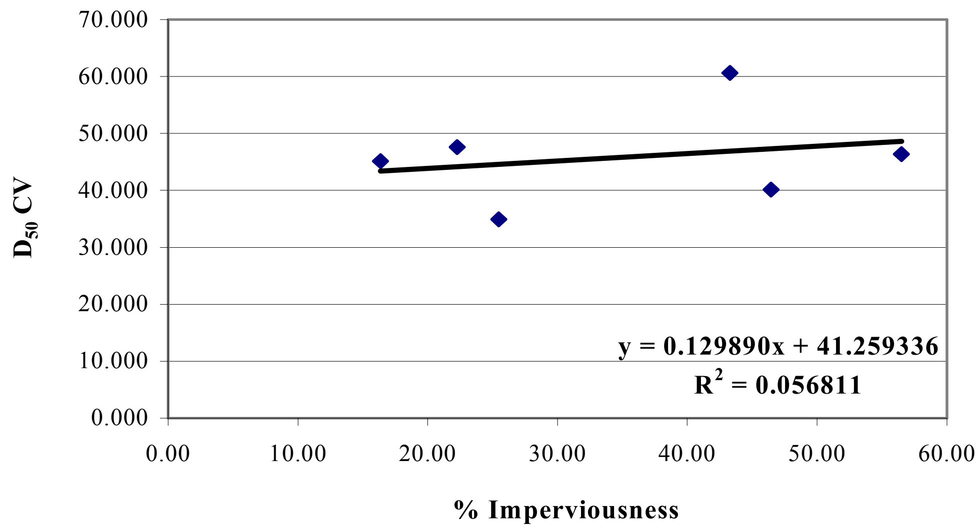


Figure 32. Comparison of D_{50} coefficient of variation of each reach and percent imperviousness; CV=coefficient of variation.

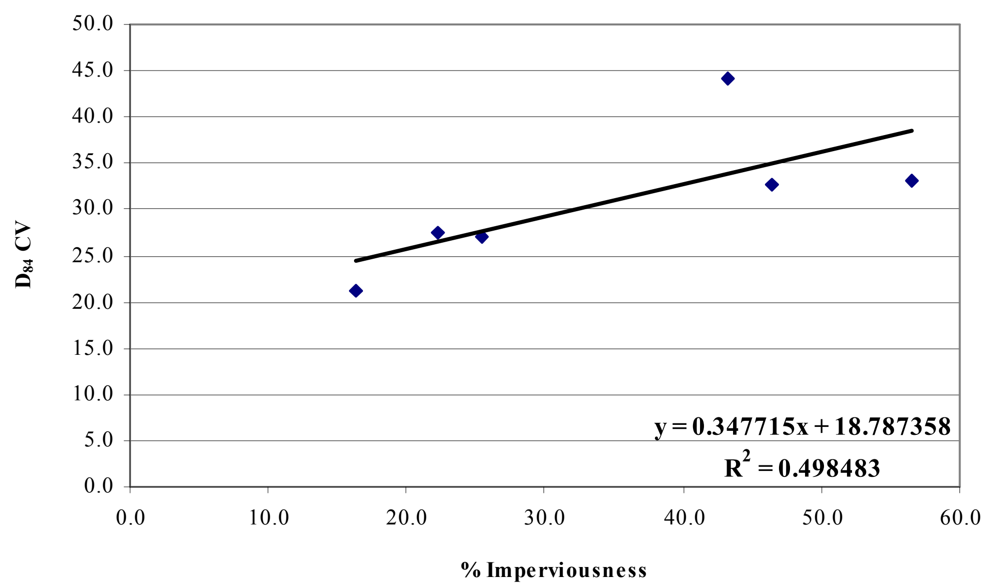


Figure 33. Comparison of D_{84} coefficient of variation of each reach and percent imperviousness; CV=coefficient of variation.

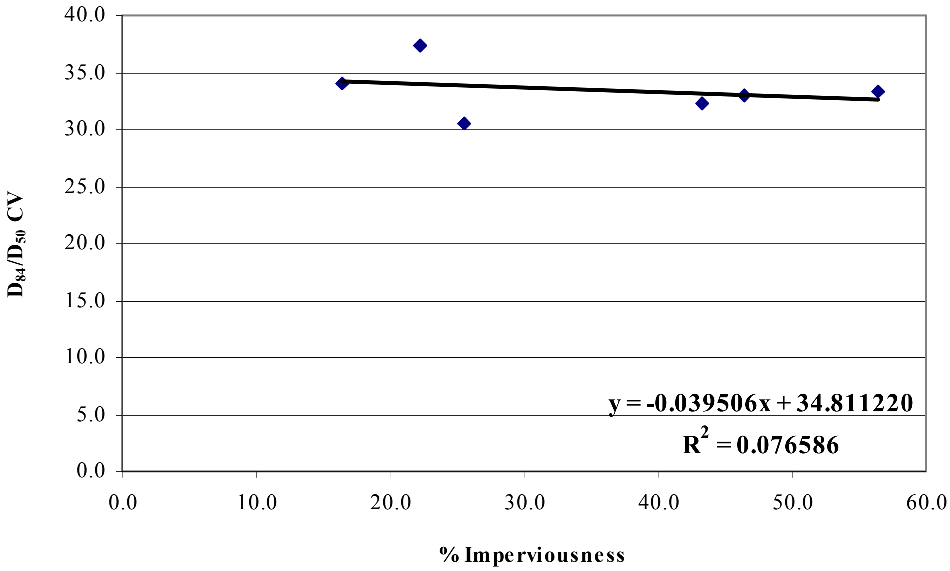


Figure 34. Comparison of D_{84}/D_{50} coefficient of variation of each reach and percent imperviousness; CV=coefficient of variation.

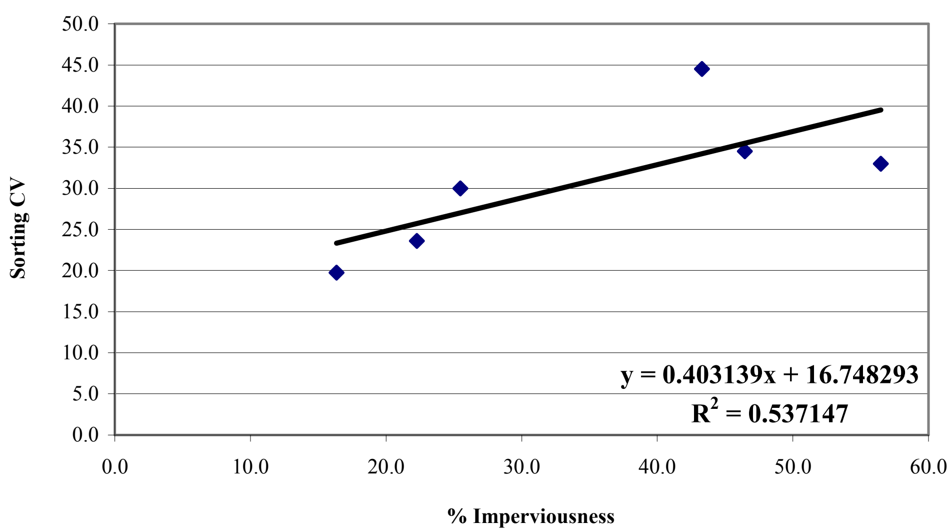


Figure 35. Comparison of sorting coefficient of variation of each reach and percent Imperviousness. CV=coefficient of variation; Sorting = $(D_{84}\text{-}D_{16})/2$.

Finally, hypothesis tests (null hypothesis: mean = 0) were carried out for all variables and percent imperviousness (Table 18). The results for all tests were the same. The p value resulted in less than .05 (95% confidence), and the null hypothesis was rejected (for each variable) (Table 18). This means that changes in percent imperviousness do not cause changes in the coefficients of variation of each of the variables. Thus, results do not show that imperviousness cause changes in stream complexity. Furthermore, the variables with the largest R^2 values are depth, D_{84}, and sorting. Width, d/D_{84}, and d/D_{50} have poor R^2 values, while wetted perimeter and the width/depth ratio have moderate values. These variables however, do not appear to have a trend with increasing imperviousness.

SLOPE COEFFICIENT TEST; NULL HYPOTHESIS: SLOPE = 0

Variable	Slope Coeff. Value	R^2	p-Value	Lower 95%	Upper 95%	Reject Null Hypothesis
Width	0.017666	0.000686	0.960722	-0.918375	0.953708	No
Depth	-0.44429	0.405587	0.173865	-1.190961	0.30238	No
Width/Depth Ratio	-0.281374	0.275625	0.284852	-0.914613	0.351864	No
Cross-Section Area	-0.116371	0.02194	0.779444	-1.194996	0.962255	No
Wetted Perimeter	0.298727	0.220991	0.346799	-0.479881	1.077335	No
Hydraulic Radius	0.438304	0.172524	0.41279	-0.894261	1.770869	No
D_{16}	-0.243407	0.068718	0.615794	-1.487337	1.000524	No
D_{50}	0.12989	0.056811	0.649246	-0.604828	0.864607	No
D_{84}	0.347715	0.498483	0.116923	-0.136459	0.831889	No
d/D_{50}	0.051724	0.00255	0.924313	-1.368311	1.471759	No
d/D84	-0.064616	0.004111	0.903952	-1.460692	1.331461	No
D_{84}/D_{50}	-0.039506	0.076586	0.595484	-0.229943	0.15093	No
Sorting	0.403139	0.537147	0.097484	-0.116366	0.922644	No

Table 18. Slope coeffiecient test for comparison of reach variables and imperviousness; 95% confidence (Figures 26-35).

Conclusion and Discussion

Stream restoration practitioners are generally lacking in resources to perform detailed stream assessments in order to determine the stability of a stream. Because of this, it is typical that a single cross-section be selected in order to describe a stream's physical and geomorphological characteristics (Rosgen, 1996, Harrelson et al., 1994). Harrelson, et al. suggests, for example, to choose a cross-section in a straight segment between two bends of a meandering stream as a reference site.

It is hypothesized in this study that single cross-sections are not adequate for describing the stream morphology of the channel adequately. To assess urbanization impacts, a worker may determine that a stream's available habitat has decreased over time based on one cross-section that has been studied over this same time period. However, loss of habitat at this cross-section may be controlled by local factors such as location next to a road crossing or bank material. The reach may in fact have adequate habitat for the species of concern. Thus, this stream may be determined 'degraded' in terms of habitat because of a lack of information of various points along the reach. The stream may itself recover from watershed urbanization or other disturbance despite localized findings (Henshaw and Booth, 2000).

To test this hypothesis, a cross-section immediately downstream of a riffle was chosen as a 'test site.' Results showed that for channel dimensions, a single cross-section did not capture the varied stream geomorphology described by the average variables. However, one cross-section does describe variables related to substrate, such as substrate heterogeneity or relative roughness, more adequately than channel dimensions. When compared to shear stress, single cross sections closely approximate the mean values.

Especially close are the values for the shear stress ratios, both based on D_{50} and D_{84}, with four and five single cross-section values (respectively) being equal to reach mean values. Furthermore, these cross-sections did not portray the high mobility of the eleven cross-sections in both Cottage Lake and North Creeks.

According to these results, it is determined that this procedure may not be adequate in describing stream's geomorphology, because it cannot capture channel heterogeneity and may not provide an accurate estimate of mean characteristics within the reach. Substrate may be more adequately described; however, it would only suffice if the goal was to gain a general understanding of the reach substrate distribution. Results from this study show, however, that single cross sections may be adequate in determining the shear stress ratio (bankfull shear stress to critical shear stress) and perhaps the bankfull shear stress. In spite of this, it is not considered practical to determine bed mobility, however. Thus, using the common procedure of carrying out one cross-section may be accurate to gain a general idea of the physical 'health' of the stream but would tend to generalize or ignore local factors. At the same time, this type of procedure could not be used to describe the range or variation of morphological variables within a reach.

This method may lead practitioners to make inaccurate decisions about a stream's geomorphology and about subsequent plans of restoration to a stream that are unnecessary. This can cause inefficient use of time and resources. However, the purpose of the assessment should be considered when determining which procedure to carry out. Though the extensive measurements carried out in this method describes in detail the channel's morphology, it is labor and time-intensive. Such results are not always necessary, and thought should be taken about the intended outcome before work is carried out.

One goal of this thesis was to explore the changes in values for typical variables used to describe stream morphology. A rigorous field procedure was carried out in order to determine which variables did in fact change from cross-section to cross-section along the length of the reach. It was found that the variables with the highest standard deviations dealt with substrate, including substrate size, relative roughness, and substrate sorting. Those that had the smallest standard deviations dealt with channel dimensions, such as bankfull depth and hydraulic radius. What was evident for all the stream sites, however, was that all stream sites showed variation in their morphology and substrate, even the most urbanized stream, Miller Creek. This was not expected, as past studies have shown that streams become more homogenized with increasing urbanization (Goodson, 2000). A finding made through the investigation of this in-stream variation may explain these results.

When looking at the substrate variation along the reach for the six streams, it was found that the range of substrate size increased for two urbanized streams – Swamp and Miller Creeks more than at the other sites. It has been found that urbanized streams have more fine material than do less urbanized streams (Goodson, 2000). This is true for these streams, although North, also highly urbanized does not seem to have as many fines. Past work also has shown that as fines increase, coarse material tends to decrease, as it moves downstream as a result of high discharge and shear stress values. The substrate distributions for these two highly urban sites show, however, that coarse material has not been completely replaced by the fines. In fact, when looking at the distribution, it appears to have a larger range than the less urbanized sites. This implies that there is supply of bed substrate from upstream of fine and coarse material. This supply of coarse material allows the stream to adjust both channel bed and morphology to keep pace with the increased discharges provided by urbanization. Thus, the hypothesized decrease in channel complexity with urbanization did not occur because these streams did not seem to be limited in the supply of coarse sediment.

Preliminary work carried out in Maryland has shown that streams in the Coastal Plain region show different results (Goodson, 2000). Generally, the bed substrate in urbanized channels tends to become finer, with coarse material taken downstream by stream flow (Goodson, 2000). As this occurs, the channel may not be able to adjust to changes in bed substrate and increased discharge, causing channel erosion and a decreased in complexity.

In the Maryland Coastal Plain area, upstream sediment supply is low or nonexistent, and thus, the channels have stopped adjusting. The main substrate supply appears to originate from bank material that is mostly made up of fine material.
In the Puget Sound Lowland region, however, upstream sediment supply appears to still exist and contribute adequately to the bed, allowing for substrate to remain at a certain level of heterogeneity. As the distributions show, bed substrate increases in fine substrate (as urbanization increases), and coarse material that flows downstream is replaced by a supply of both fine and coarse material. So here, the continued supply of coarse sediment from upstream allows the channel to continue to adjust, thus, adjusting to urbanization. Stream bed substrate does not appear to become as homogenized with urbanized as

originally expected based on past work (Goodson, 2000). (This thesis is a study of a 'shot in time,' and data is not available of what substrate was present in the past). However, data collected from this study supports this alternate theory.

The substrate distributions also show that the increasing amount of fines may affect the availability of spawning habitat, though this was no investigated in this study. At the same time, the coarse sediment contributed from upstream allow for habitat and refuge for salmon once they have spawned. Detailed substrate studies may be necessary if studying habitat availability in a certain stream.

Bed substrate adjustments may explain the lack of relationship between morphological variables and imperviousness. The hypothesis that variation of stream morphology (shown by coefficients of variation) decreased with urbanization did not hold true in this study. It is suggested that urbanization impacts to stream geomorphology may not be solely described by imperviousness but also by upstream sediment supply. As such, it is suggested that upstream sediment supply be considered as an additional independent variable by which to assess urbanization impacts to stream geomorphology and complexity.

The possibility that sediment supply and thus substrate size is a factor in determining stream morphology changes in response to urbanization may also explain another finding in this thesis. It was hypothesized that stream complexity (described by coefficients of variation) would decrease as urbanization (described as percent imperviousness) increased. The results, however, do not support this hypothesis. A clear trend only existed for bankfull depth, with the coefficients of variation decreasing with increasing percent imperviousness. Trends for D_{16} and substrate heterogeneity (D_{84}/D_{50})

existed but were relatively weak. The reason, though, for these results may be that the available upstream sediment supply allows the channel to adjust to urbanization. Thus, channel morphology changes by these adjustments, allowing for various values of complexity to exist.

In addition, this thesis shows that percent imperviousness alone is not sufficient to analyze degradation of stream complexity or stream morphology in general. This claim is supported by Henshaw and Booth (2001), in which they found that channel instability is not well predicted by either the magnitude of developed area of the rate of recent development. They found that restabilization of a channel depends on a combination of hydrologic and geomorphic characteristics in addition levels of urbanization. It is clear that percent imperviousness (as also supported by hypotheses testing) is not in itself enough to describe stream complexity and its decrease with increasing urbanization.

The final hypothesis stated that mobility would increase with increasing urbanization. Again, results disproved this hypothesis. However, only two streams showed high mobility (for 11 cross-sections), and three others showed one cross-section of each is mobile. The highly-mobile were not necessarily the most urbanized streams, and no trend appears to exist. It has been shown that upstream sediment supply still exists in these streams (especially as compared to Maryland Coastal Plain streams). A possibility for this lack of increasing mobility may be that these streams are able to adjust to the increased runoff resulting from increased urbanization. What appears to be happening is that the stream bed continues to receive upstream sediment supply and the channel changes in accordance. As it is changing, it is expected that channel erosion may occur, widening or incising the channels to accommodate for the increased runoff. These results imply that only two streams are adjusting to this increase, and the others have already adjusted to the increased runoff and are perhaps at a new state of quasi-equilibrium.

This may be a result of these two streams being developed at the time this data were collected, and that the streams had not yet adjusted to upstream watershed changes. However, the other streams, except in the most urbanized, were also being developed at the time of this data collection. Because the most urbanized stream is an older watershed, it is assumed that development that was occurring at the time was relatively low as compared to the other streams. In addition to their upstream sediment supply, the lack of stream bed mobility may be due to the amount and kind of new development, how recent the development was, and the distance between new development and stream sites. One of the most mobile streams had the most forested urban area, which would most likely help to decrease urbanization impacts. It is possible that although this may allow increased infiltration capacity as compared to other watersheds, that the amount of surrounding new development is significant and still eroding the channel.

A past study by Moglen and Beighley (2002) showed that peak discharge changed spatially with land use, and thus the location of these streams may impact their mobility. Another study by Bledsoe and Watson (2000) found that channel instability (change in stream power) was related to connectivity, and thus, distance of sites to conveyance structures, roads or bridge crossings may play a part in a stream bed's mobility. However, sites in this study were at least 50-100m downstream from any conveyance structure, but perhaps this choice of distance did not relieve the stream stability.

Another factor that influence a stream's stability is erodibility of banks and bed and riparian buffers. Henshaw and Booth (2000) showed that streams in the Puget Sound Lowland region do not consistently adjust to urbanization at the same rate, because of important differences in the determining hydrologic and geomorphic characteristics. Although the general geology and past land use of the Puget Sound area is relatively similar, local differences may affect a stream's mobility. In addition, McBride (2001) states that LWD abundance and stream complexity are most influenced by the local riparian zone. Although sites chosen for this study were determined to have vegetated riparian buffers, differences in vegetation density as well as upstream riparian buffers were not considered part of this study.

It is clear that not only levels of urbanization can describe stream impacts in watersheds that have been developed. Determining urbanization impacts to a stream is in fact a complicated process and involves understanding of both watershed- and local-scale of hydrologic, geologic and geomorphic factors as well as temporal and spatial scales of development. It is important that stream practitioners investigate a stream in detail before determining it to be degraded. An investigation should be planned according to the goals of the project, and standardized methods may not be as useful in determining which streams need to be restored. For example, if determining where to add channel control structures to a stream reach, it is important that a clear picture of the stream's mobility be understood.

Furthermore, stream restoration should be a component of watershed planning, as watershed planning should be a component of urban planning. It is important that stream restoration projects be planned in coordination with other important agencies to ensure efficient use of resources. Implementing a stream restoration project at the same time that the upstream area has been zoned for high-density development is probably not a wise course of action. Instead, stream practitioners and watershed planners may work with urban planners to allow the development to be carried out in such a way to reduce impacts to the downstream watershed. Since location and type of watershed development, in addition to hydrologic and geologic differences, may in fact play a part in how (and if) a stream degrades, holistic planning may help to avoid extensive urbanization impacts to streams about both the watershed and local scale.

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